DOCUMENT RESUME

ED 287 738 SE 048 702

AUTHOR	Owen, Dean H.; And Others
TITLE	Perception and Control of Simulated Self Motion. Final Report for the Period April 1983-March 1987.
INSTITUTION	Ohio State Univ., Columbus. Dept. of Psychology.; Ohio State Univ., Columbus. Research Foundation.
SPONS AGENCY	Air Force Human Resources Lab., Williams AFB, Ariz.
REPORT NO	AFHRL-TR-87
PUB DATE	Nov 87
NOTE	193p.
PUB TYPE	Reports - Research/Technical (143) -- Reports - Evaluative/Feasibility (142)
EDRS PRICE	MF01/PC08 Plus Postage.
DESCRIPTORS	*Aerospace Education; Aerospace Technology; Air Transportation; Aviation Mechanics; *Aviation Technology; Engineering Education; *Flight Training; *Perception; *Power Technology; Science and Society; Science Education; *Science Experiments
IDENTIFIERS	*Air Force Human Resources Laboratory

ABSTRACT

This report includes three experiment sections. The first experiment tested sensitivity to loss in altitude and demonstrated that: (1) preview effects led to adaptation; (2) sensitivity decreased with higher flow rates; and (3) sensitivity increased with higher optical texture densities and fractional loss. The second and third experiments examined the perception and control of change in forward speed and altitude, respectively. Results from the former indicated that higher levels of fractional loss led to enhanced control of a constant speed, whereas high flow and/or edge rates interfered with performance. The control of altitude change was similarly affected by the levels of fractional loss, but the negative effect of flow rate occurred only in conditions of descending flight. Theoretical implications for the ecological approach to the study of perception and control are discussed. (Author)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

U.S. DEPARTMENT OF EDUCATION
Office of Educational Research and Improvement
EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)

☒ This document has been reproduced as received from the person or organization originating it.

☐ Minor changes have been made to improve reproduction quality

- Points of view or opinions stated in this document do not necessarily represent official OERI position or policy

AFHRL-TR-87-16

ED287738

AIR FORCE HUMAN RESOURCES LABORATORY

PERCEPTION AND CONTROL OF SIMULATED SELF MOTION

Dean H. Owen
Scott J. Freeman
Brian F. Zaff
Lawrence Wolpert

Department of Psychology
Ohio State University Research Foundation
1314 Kinnear Road
Columbus, Ohio 43210

OPERATIONS TRAINING DIVISION
Williams Air Force Base, Arizona 85240-6457

November 1987

Final Report for the Period April 1983 - March 1987

Approved for public release; distribution is unlimited.

SE 048 702

AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235-5601

BEST COPY AVAILABLE

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The Public Affairs Office has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

ELIZABETH MARTIN
Contract Monitor

HAROLD G. JENSEN, Colonel, USAF
Commander

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFHRL-TR-87-16

6a. NAME OF PERFORMING ORGANIZATION
Ohio State University
Research Foundation

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
Operations Training Division

6c. ADDRESS *(City, State, and ZIP Code)*
1314 Kinnear Road
Columbus, Ohio 43210

7b. ADDRESS *(City, State, and ZIP Code)*
Air Force Human Resources Laboratory
Williams Air Force Base, Arizona 85240-6457

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
Air Force Human Resources Laboratory

8b. OFFICE SYMBOL *(If applicable)*
HQ AFHRL

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F33615-83-K-0038

8c. ADDRESS *(City, State, and ZIP Code)*
Brooks Air Force Base, Texas 78235-5601

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
61102F	2313	T3	31

11. TITLE *(Include Security Classification)*
Perception and Control of Simulated Self Motion

12. PERSONAL AUTHOR(S)
Owen, D.H.; Freeman, S.J.; Zaff, B.F.; Wolpert, L.

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM Apr 83 TO Mar 87

14. DATE OF REPORT *(Year, Month, Day)*
November 1987

15. PAGE COUNT
194

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
05	08	
06	10	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
control
ecological optics
egomotion
optical flow
self-motion perception
visual proprioception
visual psychophysics
visual simulation

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report includes three experiment sections. The first experiment tested sensitivity to loss in altitude and demonstrated that (a) preview effects led to adaptation, (b) sensitivity decreased with higher flow rates, and (c) sensitivity increased with higher optical texture densities and fractional loss. The second and third experiments examined the perception and control of change in forward speed and altitude, respectively. Results from the former indicated that higher levels of fractional loss led to enhanced control of a constant speed, whereas high flow and/or edge rates interfered with performance. The control of altitude change was similarly affected by the levels of fractional loss, but the negative effect of flow rate occurred only in conditions of descending flight. Theoretical implications for the ecological approach to the study of perception and control are discussed.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
Nancy J. Allin, Chief, STINFO Office

22b. TELEPHONE *(Include Area Code)*
(512) 536-3877

22c. OFFICE SYMBOL
AFHRL/TSR

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

SUMMARY

This report is the third in a series documenting experiments designed to assess the usefulness of visual information for flying and simulating flight for training. It is assumed that (a) visual guidance of flight is based on sensitivity to global optical variables specifying the speed and direction of self motion, and (b) control adjustments are made to achieve desirable optical conditions. Two metrics for potentially informative flow-pattern variables intrinsic to self-motion events have been isolated: (a) the distance from the eye to an environmental surface (the eyeheight, in the case of flight over flat ground) and (b) the spacing of texture elements on the surface. The experiments consist of factorial contrasts of these optical variables.

Lateral displacement of optical discontinuities perpendicular to the direction of travel is the most useful source of information for change in altitude. High initial flow rates and flow acceleration both interfere with descent detection. Sensitivity to change in speed is a function of both flow rate and illusory edge rate (speed-scaled in ground units), the latter varying with edge spacing in the direction of travel. In every case, functional variables have been fractional, rather than absolute, rates of change. Texture density is optimal for detecting change in altitude when it is four times the optimal density for detecting change in speed. Both duration of an event's preview segment and duration of the test segment itself affect sensitivity. The effects of optical variables can be observed in the slope of the initial control adjustment and in the subsequent maintenance of control cancelling a forcing function.

Two general principles have been discovered: (a) Equal-ratio increments in a functional variable result in equal-interval improvements in performance. (b) The easier the parameters of an event are to detect, the easier they are to control. Based on whether an optical variable is relevant or irrelevant to the task and whether the individual is attuned or unattuned to that variable, it can be empirically classified (a) functional (informative), (b) nonfunctional (noninformative), (c) dysfunctional (misinformative), or (d) contextual (uninformative). With practice and training, a variable can be shifted from nonfunctional to functional or from dysfunctional to contextual.

PREFACE

This work was accomplished in support of the Aircrew Training Thrust of the Air Force Human Resources Laboratory (AFHRL), Operations Training Division. Its purpose was to test theoretical hypotheses concerning the effects of optical flow variables on the perception and control of self motion. The research is intended to advance the understanding of the role of optical variables for flight simulator visual system applications.

Appreciation is extended to the following individuals at The Ohio State University: Dave Park and Bob Todd for equipment development and programming necessary for conducting the studies; Joe Damico and Mitch Giesy for programming in the analysis phase; Bert Breving, Tammy Cisco, Bill Jelinek, Ken Kaufman, Don Miller, Randy Raniero, Dave Schermer, and Danielle Sims for assistance in data collection; and Chris Oakes for assistance in preparation of this report. The Behavioral Sciences Laboratory is acknowledged for use of space and services. The authors have also benefited from the advice and encouragement of Dr. Elizabeth Martin, the AFHRL technical monitor for the project.

The project was sponsored by AFHRL under contract number F33615-83-K-0038, Task 2313-T3, Work Unit 2313-T3-31, Optical Flow and Texture Variables.

TABLE OF CONTENTS

Page

I INTRODUCTION 1

II EFFECTS OF PREVIEW DURATION, OPTICAL FLOW RATE, AND OPTICAL TEXTURE DENSITY ON SENSITIVITY TO LOSS IN ALTITUDE 9

- Method 16
- Results 18
- Discussion 21
- Conclusions 23

APPENDIX II-A: Inventory of Event and Performance Variables 25

APPENDIX II-B: Instructions 29

APPENDIX II-C: Block Order Numbers for Each Session. . . 33

APPENDIX II-D: Analysis of Variance Tables 35

III PERCEIVING AND CONTROLLING CHANGES IN THE SPEED OF SELF MOTION 43

- Method 56
- Results 59
- Discussion 68
- Summary and Conclusion 104

APPENDIX III-A: Inventory of Flight and Ground Texture Parameters 105

APPENDIX III-B: Inventory of Event and Performance Variables 109

APPENDIX III-C: Instructions 120

APPENDIX III-D: Analysis of Variance Summary Tables . . 123

IV PERCEIVING AND CONTROLLING CHANGES IN ALTITUDE 148

- Method 149
- Results 150
- Conclusions 157

APPENDIX IV-A: Inventory of Flight and Texture Parameters 160

APPENDIX IV-B: Instructions 165

APPENDIX IV-C: Analysis of Variance Tables 168

REFERENCES 180

LIST OF FIGURES

Figure Page

II-1 Percent error and mean correct reaction time pooled across sessions and preview periods for the five non-practice levels of initial fractional loss in altitude (z/z) (392 observations per point) 14

II-2 Mean reaction time pooled across sessions for the seven levels of preview period crossed with the seven levels of initial fractional loss in altitude (z/z) (336 observations per point for z/z = 0%/s, 56 observations per point for all other levels) 15

II-3 Area above the isosensitivity curve (100-Ag) as a function of fractional loss in altitude (z/z) and optical density ($z/x_g = z/y_g$), pooled over six levels of preview duration and five levels of flow rate (1,440 observations per point). 19

II-4 Mean correct reaction time as a function of fractional loss in altitude (z/z) and global optical density ($z/x_g = z/y_g$), pooled over six levels of preview duration (288 observations per point). 20

II-5 Area above the isosensitivity curve ($100-A_g$) as a function of combined pairs of preview periods, fractional loss in altitude (z/z), and optical density ($z/x_g = z/y_g$), pooled over flow rate values of A, 1.63 and 3.26 h/s and B, 6.52 and 13.04 h/s (288 observations per point). 22

III-1 Acceleration time histories showing good performance by a practiced subject attempting to counter a positive forcing function (A), and a negative forcing function (B), and then maintain a constant rate of self motion. 61

III-2 Acceleration time histories showing constant error for a positive forcing function (A) and variable error for a negative forcing function (B) produced by a practiced subject attempting to maintain a constant rate of self motion. 62

III-3 Segment of acceleration time history showing response initiation phase at point A, initial correction phase between points A and B, and maintenance phase from point B until completion of 10 s events 63

III-4 Proportion error (A) and mean correct reaction time (B) as a function of initial global optical flow rate for events representing accelerating and decelerating self motion. . . . 65

List of Figures (Continued)

III-5 Proportion error (A) and mean correct reaction time (B) as a function of initial fractional change in speed for events representing accelerating and decelerating self motion. 66

III-6 Proportion error as a function of session for events representing accelerating and decelerating self motion. . . . 68

III-7 Proportion error as a function of initial global optical flow rate and session for events representing decelerating (A) and accelerating (B) self motion. 69

III-8 Proportion error as a function of sessions and three pairs of initial edge rates for events representing decelerating rates of self motion. 70

III-9 Proportion error as a function of initial edge rate and initial flow rate for events representing decelerating self motion 71

III-10 Regression lines for controlled acceleration from reaction time until the mean time required to counter the forcing function for each session. The slope of each line is equal to the mean change in acceleration (x) during the initial corrective phase of performance 73

III-11 Regression lines for controlled acceleration from reaction time until the forcing function had been countered (at the dashed line) for each level of initial fractional change in speed of self motion. The slope of each line is equal to the change in acceleration (x) during the initial correction phase of performance 74

III-12 Regression lines for controlled acceleration from reaction time until the mean time required to counter the forcing function for each level of initial flow rate. The slope of each line is equal to the mean change in acceleration (x) during the initial correction phase of performance. . . . 75

III-13 Mean velocity produced during the maintenance phase of performance, as a function of initial flow rate for events representing accelerating and decelerating self motion. The vertical bars represent ±1 mean standard deviation in velocity. The dashed line at 192 m/s represents the initial velocity. 78

III-14 Mean standard deviation in velocity produced during the maintenance phase of performance as a function of initial edge rate and initial flow rate for events representing decelerating and accelerating self motion 79

List of Figures (Continued)

III-15 Velocity at mean reaction time and mean velocity produced during the maintenance phase of performance as a function of initial fractional change in speed for events representing accelerating and decelerating self motion. Dashed line represents initial velocity 81

III-16 Mean acceleration (A) and mean standard deviation in acceleration (B) produced during the maintenance phase of performance as a function of initial flow rate for events representing accelerating and decelerating self motion. Dashed line in panel A represents perfect performance 83

III-17 Mean acceleration produced during the maintenance phase of performance as a function of initial edge rate for events representing accelerating and decelerating self motion. Dashed line at 0 m/s^2 represents perfect performance. 84

III-18 Mean acceleration produced during the maintenance phase of performance as a function of initial fractional change in speed for events representing accelerating and decelerating self motion. Dashed line at 0 m/s^2 represents perfect performance. 85

III-19 Mean standard deviation in acceleration produced during the maintenance phase of performance as a function of session for events representing accelerating and decelerating self motion. Dashed line at 0 m/s^2 represents perfect performance. 86

IV-1 Proportion wrong direction responses and mean correct reaction time as a function of initial flow rate (s_o/z_o) for events representing ascending and descending self motion. (Numbers in parentheses indicate observations per point.) 151

IV-2 Regression lines for controlled change in altitude from reaction time until the forcing function had been countered (at the dashed line) for each level of initial fractional change in altitude. The slope of each line is equal to the change in sink or climb rate (z) during the initial correction phase of performance 154

IV-3 Mean change in altitude (z) as a function of initial flow rate (s_o/z) and edge rate (x_o/x_g) for events representing ascending and descending self motion. (Numbers in parentheses indicate observations per point.) 155

IV-4 Mean change in altitude (z) as a function of sessions for events representing ascending and descending self motion. (Numbers in parentheses indicate observation per point.). . . 156

LIST OF TABLES

Table Page

I-1 The Dependence of Optical Functionality (Informativeness) on Task Relevance and Attunement 5

II-A-1 Inventory of Event and Performance Variables 26

II-C-1 Block Order Numbers for Each Session 34

II-D-1 Analysis of Variance for Descent Events 36

II-D-2 Analysis of Variance for Level Events. 39

II-D-3 Analysis of Variance for Area Above the Isosensitivity Curve. 41

III-1 Proportion Error for Deleted Subjects. 59

III-2 Slope of the Initial Onset Ramp as a Function of Initial Fractional Change. 76

III-3 Summary of Maintenance Variables 89

III-A-1 Inventory of Flight Parameters 106

III-A-2 Inventory of Ground-Texture Parameters 108

III-B-1 Inventory of Event Variables 110

III-B-2 Inventory of Performance Variables 114

III-D-1 Analyses of Variance for All Events. 124

III-D-2 Analyses of Variance for Accelerating Events 128

III-D-3 Analyses of Variance for Decelerating Events 137

IV-A-1 Inventory of Flight Parameters 161

IV-A-2 Inventory of Ground-Texture Parameters 164

IV-C-1 Analyses of Variance 169

CHAPTER I

INTRODUCTION

Dean H. Owen
The Ohio State University

The present research program is concerned with determining the informational support needed for detecting and controlling self motion, under the assumption that locomotor goals are achieved by effective control of what is perceived. Broadly conceived, the effort involves two stages: (a) mathematical isolation of potential sources of visual information for self-motion perception conveyed by the structure of the global optical flow pattern, followed by (b) tests of the effectiveness of the variables for detecting and controlling self motion.

Extrinsic versus intrinsic variables. Self motion can be scaled in metrics which are either _extrinsic_ to or _intrinsic_ to the event under consideration. Extrinsic metrics are _arbitrary_ in the sense that the units of measurement were derived to provide standards that are applicable over a variety of situations (e.g., feet or meters per second, miles or kilometers per hour, knots, degrees per second). Intrinsic metrics are _nonarbitrary_ in the sense that the units of measurement are derived directly from characteristics of the event. Since motion of the self is relative to the surrounding surfaces, intrinsic metrics can be derived from measures that relate to the _self_, to the _environment_, or to both.

All of the above metrics have _mathematical reality_ in that they can provide consistent systems for describing events. In the study of visual sources of information, we are interested in those that have _optical reality_; i.e., those that index change and nonchange in the structure of available ambient light.

An individual's path speed can be self scaled in terms of the distance from the self to an environmental surface. This variable has an optical reality in that it is a multiplier on the angular velocities in every direction in the optic array. Hence it indexes _global_ optical flow rate. For cases of motion over a ground surface, the distance from the eye to the ground directly below (the individual's eyeheight) has an additional kind of optical reality because the optical horizon is always at the observer's eyeheight. When available, the horizon thus provides a visible referent for eyeheight-scaled changes in the optic array.

The size and spacing of environmental elements can also serve as a metric for self motion. An individual's path speed can be scaled in terms of the distance between edges, intersections of edges, or objects on the ground. Two examples having optical reality are (a) change in optical density, which is specific to change in altitude scaled in ground units, and (b) edge rate, which is specific to forward speed scaled in distance between ground elements. (Cases a and b both assume regular or stochastically regular ground-element spacing).

Sensitivity versus control. Finally, having isolated potential sources of visual information, we are interested in determining which optical variables have _psychological reality_; i.e., which are actually informative and for what purposes. The empirical issue of the psychological effectiveness of optical variables and invariants can be divided for research purposes into (a) the _sensitivity problem_ (assessing perceptual skill) and (b) the _control problem_ (assessing skill in effectively controlling optical transformations in ways that result in appropriately guided locomotion). Given the large number of potentially informative variables, it is strategically important to eliminate those to which observers are not sensitive, by conducting judgment experiments in which the optical variables are rigorously controlled, before turning over to the individual the active control of those variables determined to be perceptually effective.

The approach outlined above eliminates some thorny problems that have plagued theorists. The assumption that self-motion perception is anchored to higher-order relations means that particular kinds of prior knowledge need not be assumed. The individual need not know or estimate absolute sizes, distances, or rates in any arbitrary metrics. If self-motion perception is based on information intrinsic to the event, the only assumption that needs to be made concerning prior experience is that an individual can learn to attend to and control informative optical variables.

Global optical variables are expressed in terms of ratios of lower-order environmental variables (e.g., altitude, sink rate, path speed and slope, ground-unit size and spacing) and apply to every locus in an optic array. Two optical variables are physically linked whenever the same environmental variable appears in the expressions for both (Warren & Owen, 1982). In addition, optical variables can become linked or unlinked as an event unfolds, as some variables change from invariant to varying, or vice versa, during the event. These linkages complicate the tasks of experimental design and analysis, often making traditional factorial designs inappropriate. Linkages must be dealt with, rather than avoided, since an understanding of the dynamic interrelationships among sources of information is propaedeutic to an understanding of the active control of these variables during self-guided locomotion. The very fact that two variables formerly linked have become unlinked, or vice versa, may be information for a change in the speed, heading, or even safety of self motion.

Functional versus contextual variables. A pattern of results has evolved from a series of experiments which suggests that there are two classes of event variables influencing sensitivity to changes in self motion. These classes will be called *functional* and *contextual* variables.

A functional variable is a parameter of an optical flow pattern used to select and guide a control action. If the variable is specific to the event parameter that the individual was instructed to distinguish or control, the action is considered correct or effective. (Actions are scored relative to the task demands and the stimulation available.) Results to date indicate that functional variables are of an order high enough to be completely relative (e.g., not specific to either absolute optical or event variables). Thus, an individual need not know absolute size, distance, speed, or flow rate to be sensitive to change in speed or altitude. To date, functional variables have been exclusively fractional rates of change, but this may be a result of the tasks used.

Contextual variables are those optical parameters which influence sensitivity to a functional variable. A subcategory might be called support variables because they are essential to perception of the event. There must be some optical discontinuity (i.e., difference in the optic array) in order to manifest flow-pattern changes, for example. Other variables, like preview time or cyclic change, are not essential, but can affect functional sensitivity. Some contextual variables are irrelevant to the task but have an interfering effect; for example, the higher the flow and/or edge rate, the poorer the detection of change in altitude and speed.

The operational distinction between the two classes is evident in the structure of the psychophysical functions: (a) Functional variables affect performance asymptotically. That is, increasing the magnitude of a functional variable results in increasingly better performance; decrease leads to increasingly poorer performance. These functions tend toward linearity when the functional variable is logged. Equal-ratio increments in the variable produce equal-interval improvements in performance, at least in the middle range of sensitivity. Ceiling and floor effects may bend this function into a cubic form. (b) In contrast, contextual variables reveal an optimum level of performance; hence, they have a quadratic form. Very low or high flow rates, optical densities, or preview periods result in poorer performance than do values in the middle range. In some cases, a contextual variable has shown no effect at all.

Different levels of lower-order environmental or optical variables can produce the same higher-order functional change. If performance is optimized at a constant level of one contextual variable (e.g., flow rate) but at progressively different levels of a second contextual variable (e.g., flow acceleration), there is an indication that the first variable is more basic and the second is subsidiary or auxiliary. Whether the first is basic in terms of the perceptual mechanism or in terms of the perceptual task will require some empirical effort. We have generated evidence that the optimal level of texture density is four times as high for detecting loss in altitude as for detecting loss in speed; i.e., it is task specific. Note that since the task requires control of optical variables, task specificity translates directly to information specificity. Because the functional information for detecting change in altitude depends on the lateral spacing of elements, whereas information for speed depends on spacing in the direction of travel, both can be optimized simultaneously by making forward spacing four times greater than lateral spacing. The point is that multiple optical variables may be optimized for multiple maneuvers with the same scene content.

Note that this classification system is empirically based. It is independent of our distinction between primary and secondary variables, which is an experimental design distinction (see Warren & Owen, 1982). Also note that a given optical variable could be either a functional or a contextual variable, depending on the task. Fractional change in flow rate is functional for change in speed, but contextual for detecting change in altitude. High flow and edge rates misperceived as indexing acceleration become functional variables, in contrast with their role as contextual variables during veridical perception of acceleration.

The contingency matrix shown in Table I-1 represents a more complete systemization of the possible relationships between the individual and optic array variables specifying self motion. As a general working hypothesis, an optical variable can be considered task relevant if the self-motion variable to be detected and/or controlled (e.g., speed, change in altitude, path slope) appears in the mathematical description of the optical variable. If so, the variable is at least potentially informative. (Note that a variable may take on different values during different events, but may vary or remain invariant within an event.)

Once an optical variable has been isolated mathematically and operationally, the empirical task is to determine the attunement of an individual to the variable. That is, under what circumstances does potential visual information become effective? Attunement may vary as a result of genetically endowed perceptual mechanisms, the effects of perceptual set or learning on selective attention, or the effects of adaptation to sustained stimulation.

Table I-1

The Dependence of Optical Functionality (Informativeness) on Task Relevance and Attunement

		Individual	
		Attuned	Unattuned
Optical Variable	Task relevant	Functional (Informative)	Nonfunctional (Noninformative)
	Task irrelevant	Dysfunctional (Misinformative)	Contextual (Uninformative)

The *functional* nature (i.e., the *informative* value) of an optical variable is operationally defined relative to demands on both the individual and the environment. The adequacy of information depends both on the availability of the information relevant to the task and on the sensitivity of the individual to the optical variable.

We have found that fractional change in global optical flow rate is the functional information for loss and gain in self speed. Fractional change in speed is a global multiplier on the lateral motion of optical discontinuities in the perspective texture gradient extending to the horizon. Change in this optical "splay" angle is the most functional information we have found so far for detecting and controlling altitude.

When an optical parameter is not relevant to the task, but performance measures indicate that the individual was attuned to the variable, it may be considered *dysfunctional* or *misinformative*. When self speed is constant and the spacing between edges is exponentially reduced, acceleration is reported and speed is reduced under instructions to hold speed constant. These findings indicate that edge-rate gain is functional even though it is irrelevant to the detection and control tasks. High constant flow and edge rates are also misperceived as specifying acceleration following the onset of an event.

An optical variable may be *nonfunctional* because the magnitude of the variable is too low to be detected. A variable which is functional at higher levels may be below threshold at lower levels. It is important to know whether the levels of functional variables encountered in real-world self motion are above or below threshold, as indicated by experimental tests. Thresholds vary, of course, with perceptual learning and can be used as a criterion for training effectiveness.

A variable which is potentially informative and well above threshold may, however, be *nonfunctional*. Global optical flow acceleration accompanies approach to a surface at a constant speed; therefore, it could be useful for detecting loss in altitude. Eliminating flow acceleration by decelerating at exactly the rate necessary to hold flow rate constant either has no effect on descent detection or may even result in poorer sensitivity in some cases. Hence, a potentially informative variable is *noninformative*.

Lastly, variables which are not relevant to the task and to which the individual being tested is not attuned are considered *contextual*. They may be a necessary accompaniment of the event (e.g., some level of optical density is required for self-motion perception), but they are *uninformative* with respect to the task. Low flow and edge rates have no effect on the control of speed; edge rate has little effect on altitude control.

As new potentially informative optical variables are isolated, the framework shown in Table I-1 should provide a structure for generating and testing hypotheses about the usefulness of a particular variable in a particular task. In addition, the framework should provide a means for determining where the effects of learning, set, and adaptation should be expected. Improvement in sensitivity to task-relevant information and reduction in attention to irrelevant information with instruction and practice should make some variables more informative and some less misinformative. In support of these general principles, the negative effects of high flow and/or edge rates on sensitivity to change in altitude and speed are reduced with training and practice, while performance indexed by functional fractional variables improves.

CHAPTER II

EFFECTS OF PREVIEW DURATION, OPTICAL FLOW RATE, AND OPTICAL TEXTURE DENSITY ON SENSITIVITY TO LOSS IN ALTITUDE

Dean H. Owen and Scott J. Freeman
The Ohio State University

Interest in the problem of effects of immediately preceding event variables on sensitivity to change in self motion arose from two sources: (a) our own studies of sensitivity to change in the speed of one's own motion (Owen, Warren, Jensen, Mangold, & Hettinger, 1981; Owen, Wolpert, & Warren, 1984; Tobias & Owen, 1984; Warren, Owen, & Hettinger, 1982) and to differences in direction, particularly distinguishing loss in altitude from level flight (Hettinger, Owen, & Warren, 1985; Owen et al., 1981; Wolpert & Owen, 1985; Wolpert, Owen, & Warren, 1983); and (b) the work of Denton (1973, 1974, 1976, 1977) on adaptation to forward speed during driving.

Our studies consistently showed "false alarm" rates (e.g., reporting "acceleration" or "deceleration" given constant speed; reporting "descent" given level flight) clustered around 20%. Since all of our events were initiated with a change in speed or altitude already in progress, the false alarms may have resulted from event-onset effects. Runeson (1974, 1975) found distortions of perceived speed when an event begins with an object already moving at constant speed, as contrasted with the case of motion starting from stop and accelerating to a constant speed. When a pilot emerges from cloud cover and makes visual contact with the ground, or when a pilot or driver looks up from the instrument panel, exposure occurs to optical flow in progress. Since this is in fact an optical acceleration (from no flow to some flow rate), it would not be surprising that the mechanisms underlying self-motion perception would show onset effects that take time to disappear. If so, increasing the duration of the events should reduce false alarms.

Accordingly, we varied event duration from 3 to 10 s in an experiment requiring observers to distinguish self acceleration from constant speed after they had watched the entire event (Owen et al., 1984). As predicted, reports of "acceleration" to constant-speed events dropped markedly with increase in duration. In contrast, descent-detection accuracy improved by only a few percentage points over durations of 2, 4, and 8 s (Hettinger et al., 1985).

Denton (1973, 1974, 1976) found a quite different effect of longer-term exposure to the flow pattern; namely, that some individuals adapt to self-motion stimulation. If asked to maintain a constant speed, they continually increase their speed to an asymptotic value. Time to reach asymptote, as well as the asymptotic value, varies with the initial speed and from person to person.

Our concern for the effects of the segment of a self-motion event preceding the test segment was that preview duration might interact with any variable that affected difficulty of detecting changes in self motion. In all of our manipulations of optical variables, we have found that reaction time indexes difficulty. That is, when error rates are high, reaction times are long. We have found no speed-accuracy tradeoffs. This means that levels of any variable which make detection more difficult will have longer reaction times associated with them. Event-onset effects would be more prominent when reaction times (hence, _effective_ event durations) are short, whereas adaptation effects will be more dominant as reaction times increase. These two phenomena, then, have the potential to distort the psychophysical relationships in which we are primarily interested: (a) the log-linear relation between performance and the _functional variable_ for a task; i.e., the variable to which the individual is attending (equal-ratio increments in this variable should produce equal-interval improvements in performance); and (b) the horizontal relation between performance and a _contextual variable_; i.e., a variable available but not attended to in performing a given task.

Our first attempt to address these issues involved adding a 5-s preview of constant speed to events in a preliminary experiment on deceleration detection (Tobias & Owen, 1984). The 5-s preview before the deceleration test segment resulted in lower error rates and shorter reaction times than the 0-s preview condition in which deceleration was initiated at the beginning of the event. While this experiment was in progress, we discovered an unpublished experiment by Denton (1973, 1974) in which he varied the duration of a constant-speed segment (10 versus 120 s) before initiating an increase or decrease in speed. The observers' task was to press a button when acceleration or deceleration was first noticed, and they were told before each trial which to expect. (Denton explicitly assumed that an objective measure was not possible, so no accuracy scores were available.) Change in speed (x) was a constant 10% of the initial speed, which ranged from 5 mi/h to 80 mi/h, using a doubling series except for the inclusion of 60 mi/h. Only individuals having visual self-motion aftereffects of long duration were used. The results revealed that (a) reaction times for deceleration events were longer following the 120-s preview than the 10-s duration; (b) the reverse was true for acceleration; and (c) reaction times were very long for slow speeds, shorter for the medium speeds, and increased slightly for the highest speeds. The first two findings suggest that adaptation to constant speed (manifested by an apparent slowing prior to the onset of the test segment) leaves the perceptual system in a state such that by 120 s deceleration has less contrast than at 10 s, whereas acceleration has greater contrast than at 10 s.

Our finding of faster deceleration detection from a 0-s to a 5-s preview, coupled with Denton's finding of slower detection from a 10-s to a 120-s preview, suggested that reaction time would be shortest somewhere in the midrange. Therefore, we replicated Denton's optical flow conditions with our visual simulation system, using preview periods of 0.0, 1.25, 2.5, 5, 10, 20, and 40 s (Owen, Hettinger, Pallos, & Fogt, 1985). The 40-s maximum was used for testing efficiency, since the adaptation effect observed by Denton was 80% complete by this time. Our observers distinguished deceleration from constant-speed events, so that accuracy could be scored. As in Denton's experiment, deceleration was constant and equal to 10% of the initial speed.

Relatively complex interactions among event type, initial flow rate, and preview duration were observed. The most pronounced was an effect for deceleration at the highest flow rate (80 mi/h = 26.1 h/s): For preview periods of 2.5 and 5 s, error rates increased to 80%. This finding indicates that our video system does not simulate deceleration well at very high flow rates. The specificity of the effect to intermediate preview periods is curious, and may have something to do with event-onset effects. That is, the apparent deceleration due to recovery from apparent (onset) acceleration for preview durations of 0 and 1.25 s may sum with the effect of actual deceleration to make sensitivity to deceleration seem greater for short previews. If this interpretation is correct, onset effects may have run their course by some time between 1.25 and 5 s when the initial flow rate is very high.

The most important result was evident in pooling over all preview durations (omitting the highest flow rate because of the pronounced interaction). Reaction times showed the same pattern as Denton found; i.e., they were shortest for the intermediate flow rates. The unexpected result was that accuracy was poorest for the midrange flow rates. This was the case for both constant-speed and deceleration trials, and therefore not a result of shift in frequency of using the two reports over the various flow rates. Taken together, reaction times and errors indicate a speed-accuracy tradeoff. We did not find the expected result of poorer accuracy with shorter previews (anticipated to be due to event-onset effects), or with longer previews (predicted to be due to adaptation).

We know from an earlier study that initial fractional loss in flow rate should be the functional optical variable for deceleration detection (Owen et al., 1981), and it was always 10%/s in the preview experiment. Preview duration should be a contextual variable, and need have no effect on either sensitivity or information acquisition time. Yet, for some reason(s), observers take longer under conditions that earlier studies led us to expect to be more difficult, and, possibly as a result of taking longer, are more accurate.

To test the generality of this phenomenon, we conducted two experiments assessing the effect of preview duration on detection of loss in altitude, a self-motion domain where we know that flow rate has a deleterious effect on sensitivity; i.e., the higher the flow rate, the greater the error rate (Hettinger, 1987; Hettinger & Owen, 1985; Wolpert et al., 1983).

The first experiment (Johnson & Owen, 1985) was designed to choose levels of fractional loss in altitude for the second (Owen & Freeman, 1987), since this was known to be the functional event variable for descent detection (see Owen et al., 1981). Decreasing fractional loss increases difficulty, and we have found in a variety of situations that a variable may have an effect only at higher levels of difficulty, then magnify in influence as difficulty increases further (Hettinger et al., 1985; Tobias & Owen, 1984; Wolpert & Owen, 1985). Flow rate was held constant at 1 h/s, which was slow enough that it should have a minor effect on descent detection. The 1-h/s flow rate also resulted in fractional losses in altitude ($\dot{z}/z$ in %/s)[1] and path slopes ($\dot{z}/\dot{x}$ in %) which were identical at seven levels and constant throughout each event: -0.0 (for level flight), -0.625, -1.25, -2.5, -5.0, -7.0 (for practice trials), and -10.0. Preview segments consisting of level constant-speed flight were identical to those in the Owen et al. (1985) deceleration-detection experiment. An acoustic tone sounded at the beginning of the test segment. The observer's task was to determine whether level or descending self motion was represented during the 10-s test segment of each event. Twenty-four male undergraduates participated in two 1-h test sessions each.

Figure II-1 shows the decreasing error rates and reaction times that result with increasing levels of a functional variable. Accuracy reveals a floor effect at the high end of the range, and reaction time shows a ceiling effect at the low end. As shown in Figure II-2, reaction times evidence the now-familiar quadratic relation over preview durations, with the shortest times in the midrange and longer times beyond 5 s. The results for accuracy were clustered into two patterns based on difficulty. For the higher levels of fractional loss ($\dot{z}/z$ = -5, -7, and -10%/s), error rates were essentially the same for all preview durations. For the lower levels of fractional loss and for the level trials ($\dot{z}/z$ = 0.0, -0.625, -1.25, -2.5%/s), error rates were

---

[1] A dot over a symbol indicates a derivative with respect to time.

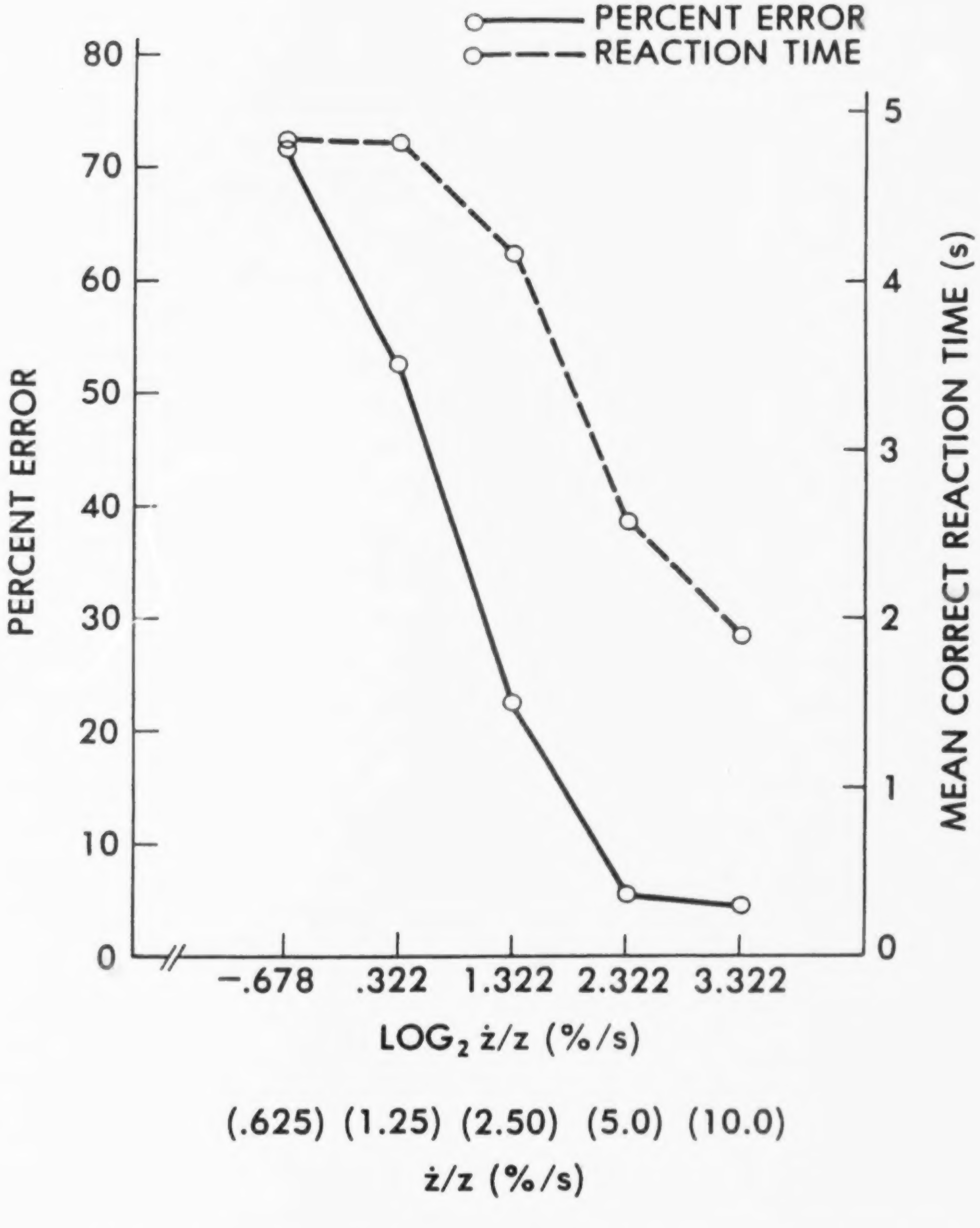

Figure II-1. Percent error and mean correct reaction time pooled across sessions and preview periods for the five non-practice levels of initial fractional loss in altitude ($\dot{z}/z$) (392 observations per point).

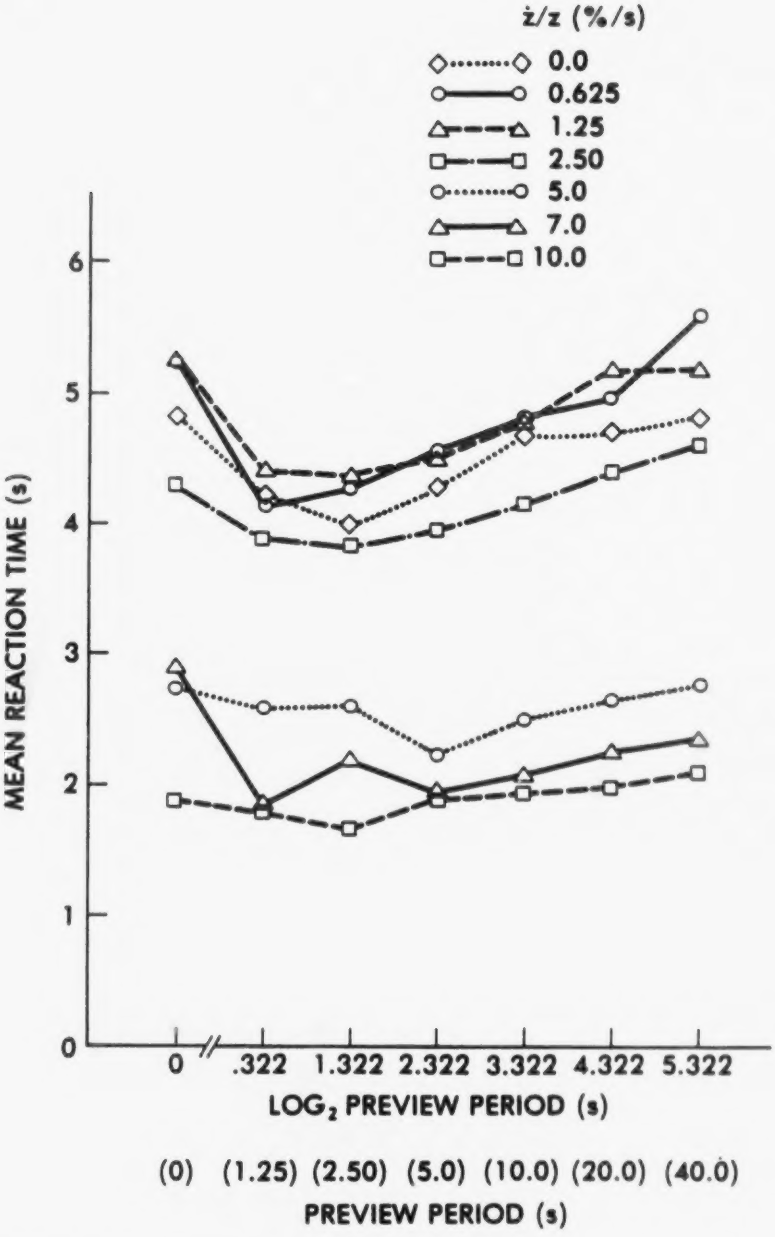

Figure II-2. Mean reaction time pooled across sessions for the seven levels of preview period crossed with the seven levels of initial fractional loss in altitude ($\dot{z}/z$) (336 observations per point for $\dot{z}/z$ = 0%/s, 56 observations per point for all other levels).

slightly greater for the midrange of preview times. The results suggest a speed-accuracy tradeoff for difficult events, but the pattern is not as strong as in the Owen et al. (1985) deceleration experiment.

The second experiment, reported here, was designed to test for the interaction of the functional variable for descent detection; i.e., fractional loss in altitude ($\dot{z}/z$), with three contextual variables: (a) duration of a preview period representing level flight, (b) global optical flow rate ($\dot{s}/z$), and (c) global optical texture density (z/x_g, z/y_g). All levels of the four variables were chosen from previous studies in which preview-period duration was manipulated.

Method

Apparatus. A special-purpose digital image generator (see Yoshi, 1980) produced real-time perspective transformations of a scene displayed by a Sony Model KP-7240 video projection unit. The sampling rate of 30 frames/s for scene generation matched the scanning rate of the video system. The test events represented self motion over a flat, rectangular island extending 30.72 km parallel to the direction of simulated travel (x dimension). The lateral extent of the island perpendicular to the direction of travel (y dimension) and the lateral ground-texture density were determined by the spacing of the 19 edges running parallel to the direction of travel. Ground-texture density in the x dimension was determined by filling 1.5-m strips perpendicular to the direction of travel in the same color to achieve the desired spacing. The resulting texture blocks, representing fields on the island, were randomly assigned four earth colors (light green, dark green, light brown, and dark brown), with the constraint that no two adjacent texture blocks could have the same color. The region above the horizon was pale blue, and the nontextured region surrounding the island was dark gray.

The person being tested was seated on an elevated chair 2.43 m in front of the screen, with a viewpoint at the level of the horizon, which was 1.95 m above the floor at the screen's center. The screen was 1.5 m in width and 1.125 m in height, producing a visual 34.3 deg by 26.1 deg. Observers indicated their categorization of an event by pressing one of two buttons. A PDP 11/34 computer controlled the sequencing of the events and recorded performance. Reaction time was measured from onset of the test segment of an event to initiation of a response.

Design. Based on the results of the preliminary experiment (Johnson & Owen, 1985), fractional sink-rate (z/z) values of -1.25, -2.5, and -5.0%/s were chosen for the second experiment since both error rate and reaction time continued to index difficulty over these levels. Some consideration was given to including the -0.625 level, but we purposely decided not to use a level of difficulty beyond which descent would be detected on fewer than 50% of the trials. Fractional loss in altitude and flow rate were both constant throughout each event. The global optical flow rates ($\dot{s}/z$) were identical to those used in the Owen et al. (1985) deceleration-detection experiment: 1.63, 3.26, 6.52, 13.04, and 26.08 h/s. Except for dropping the 40-s duration, preview periods were identical to those used in the deceleration-detection and preliminary descent-detection experiments: 0, 1.25, 2.50, 5.00, 10.00, and 20.00 s. The 40-s duration was eliminated, since Johnson and Owen (1985) found that the trend from 20 to 40 s simply continued the decreases in error rate and reaction time observed from 10 to 20 s. The time saved by not including the 40-s preview allowed a complete replication of the remainder of the design during the four 1-h test sessions. Rather than simply repeating identical events, global optical texture density in the forward (z/x_g) and lateral (z/y_g) directions was varied over two levels: 1 and 4 g/h. (Note that areal density is the multiple of orthogonal linear densities.)

Tobias and Owen (1984) found a density of 1 g/h in both dimensions (produced by square fields on the ground, the sides of which equaled the simulated eyeheight) to be optimal for distinguishing decelerating from constant-speed self motion. Hettinger et al., (1985) used square fields to produce optical densities of 1, 4, and 16 g/h, and found that descent detection optimized at 4 g/h. Their second experiment showed no difference in performance between densities of 2 and 4 g/h. Since density is of considerable theoretical (How does a variable with no change over time affect event perception?) and practical (What density is best for training of a particular maneuver?) interest, we wanted to determine whether we could replicate the initial findings of (a) better descent detection at 4 g/h and (b) a different optimum level from that for deceleration detection (1 g/h). Except for a number-identification task performed during half of the sessions to test the effect of requiring attention in the ground region of the flow pattern, the procedure was the same as in the Johnson and Owen (1985) experiment. (The identification task made no difference.)

Participants. Forty-eight undergraduate males participated in four 1-h test sessions each in order to fulfill an extra-credit option of an introductory psychology course. All observers claimed no previous simulator or piloting experience.

Results

The effect of preview duration on reaction time was essentially the same as in the Owen et al. (1985) deceleration-detection experiment, with the shortest times occurring over the midrange durations (1.25 to 5.00 s). As expected, sensitivity to descent was increasingly poorer the higher the flow rate. An increase of almost 15% in "level" reports over the range of flow rates used was accompanied by a decrease in level-trial reaction times of 1.5 s. Figures II-3 and II-4 show that density had a great effect on sensitivity and reaction time, favoring 4 g/h when fractional loss was low; but the effect was considerably reduced as fractional loss increased. (The parameter A_g is an unbiased estimate of sensitivity (Pollack, Norman, & Galanter, 1964). The area above the isosensitivity curve ($100-A_g$) is plotted to be comparable to error rate.)

A major motivation for the study was the possibility of interactions among preview duration and global optical variables. The sensitivity results show good reason for our initial concern. The four-way interaction of preview period by fractional loss by density by flow rate was significant for the descent data, but several qualifying comments are in order before discussing these complex effects. At this level of analysis, the data are spread quite thin, and plots of the means are fairly noisy. By pooling over pairs of levels of preview durations and flow rates, as well as dropping the highest flow-rate

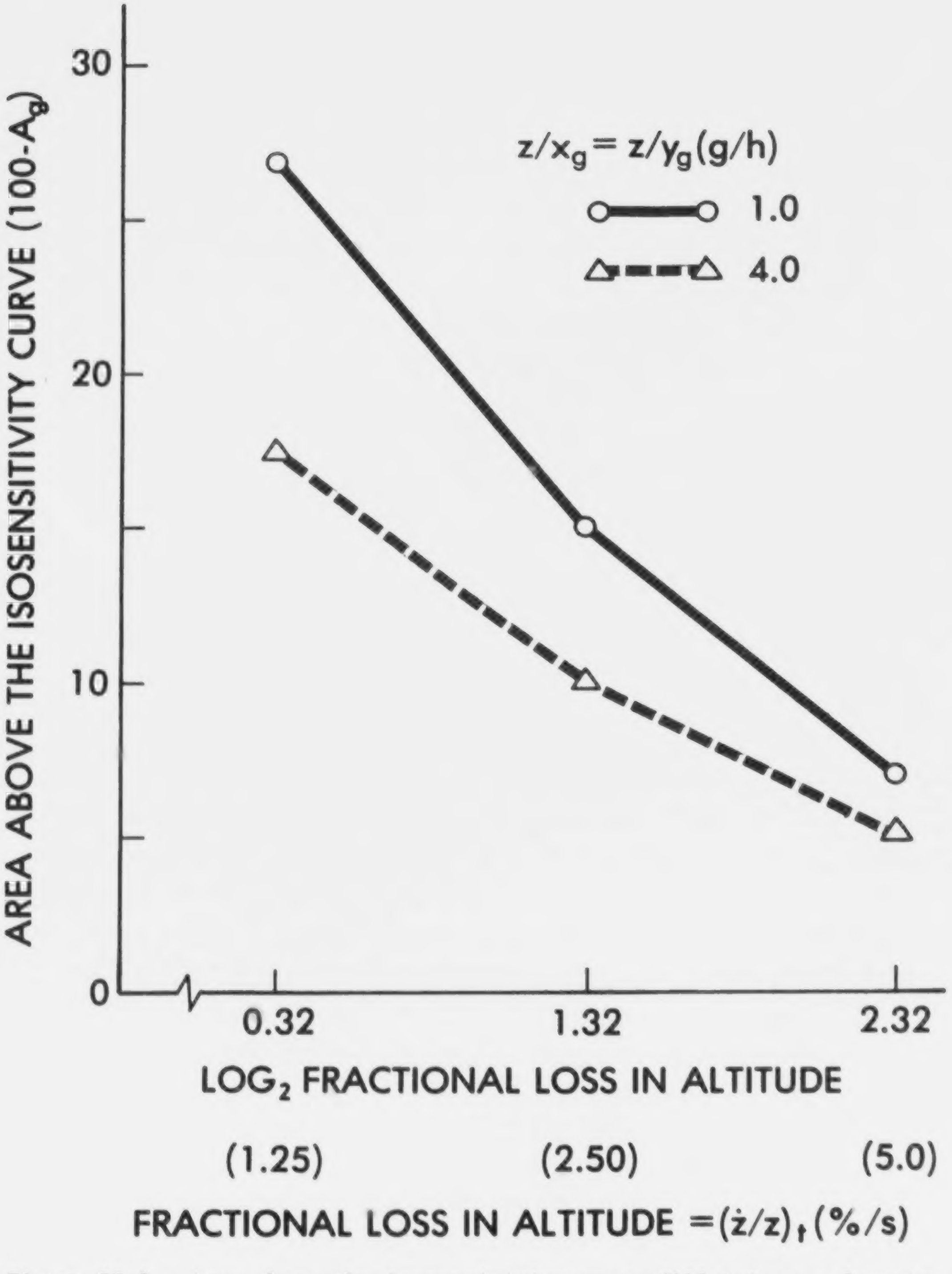

Figure II-3. Area above the isosensitivity curve (100-Ag) as a function of fractional loss in altitude ($\dot{z}/z$) and optical density (z/x_g - z/y_g), pooled over six levels of preview duration and five levels of flow rate (1,440 observations per point).

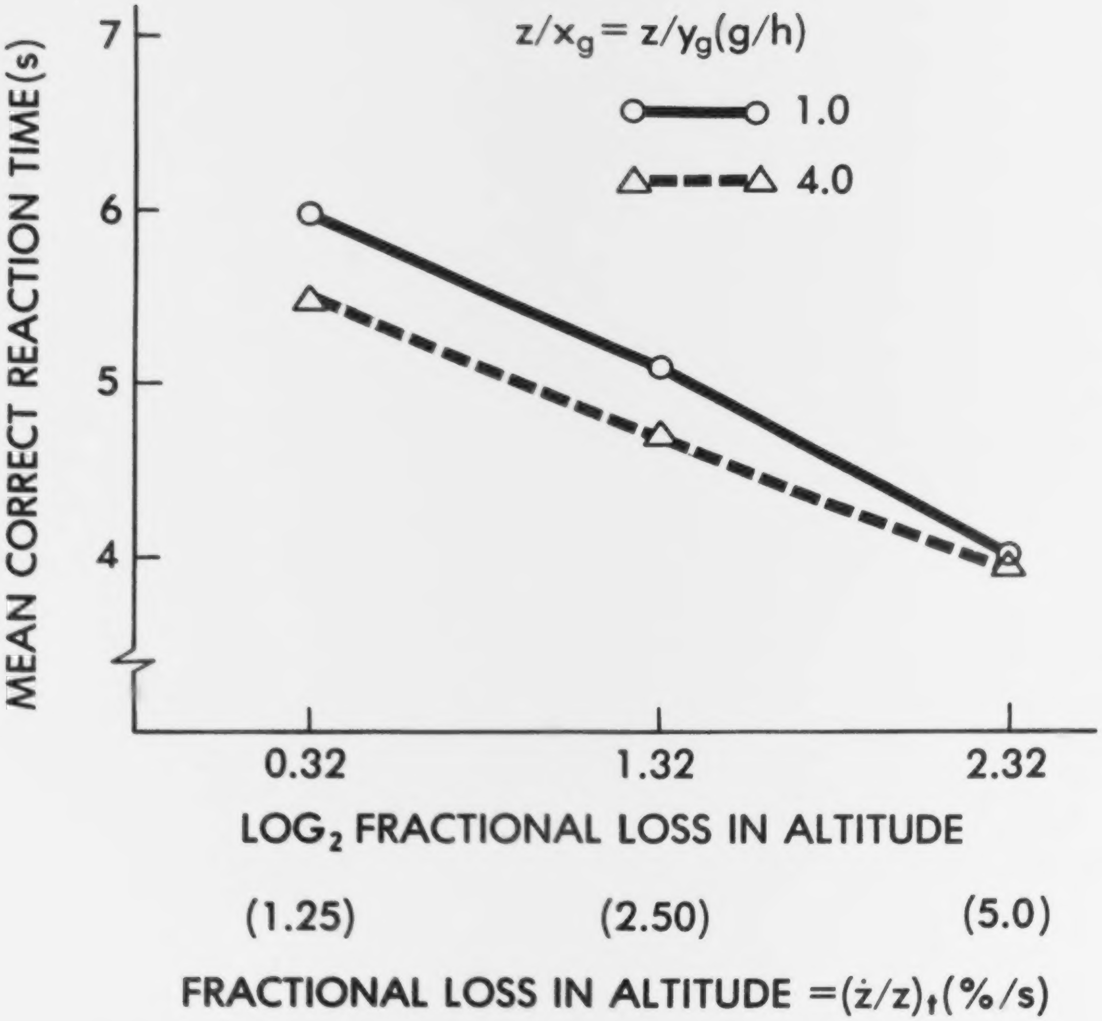

Figure II-4. Mean correct reaction time as a function of fractional loss in altitude ($\dot{z}/z$) and global optical density ($z/x_g = z/y_g$), pooled over six levels of preview duration (288 observations per point).

level, a reasonably coherent and interpretable structure emerges. (The 26.08-h/s flow rate resulted in a complex interaction of its own: Relative to the 13.04-h/s flow rate, sensitivity was better at low levels of difficulty, no different at medium levels, and poorer at the highest levels. Apparently, the poor simulation of a flow rate this high by our video system, as observed in the Owen et al. (1985) experiment, extends to descent detection as well.)

Figure II-5 shows the four-way interaction in two panels for clarity. First note that the lowest four lines in Figure II-5A and the lowest three lines of Figure II-5B are relatively flat. When the difficulty level is low (10% or below), preview duration has essentially no effect on sensitivity. This pattern extends to medium levels of difficulty (15 to 20%), but only for short and medium previews when flow rates are relatively low and only for medium and long previews when flow rates are relatively high. When the difficulty level is highest (28 to 37%), preview duration has a positive effect on sensitivity over the entire range explored.

Discussion

The various levels of fractional loss and density contribute in combination to difficulty in detecting descent, and the interpretation is simplified considerably by dealing with the effects of preview duration and flow rate in concert. Since there is no evidence of a negative event-cnset effect, the explanation of the interaction will concentrate on the effect of adaptation to the rate of optical flow.

Two types of background information are needed for this account: (a) Denton (1976, 1977) found that for those individuals who adapt to forward self motion, the faster the simulated speed, the steeper the adaptation curve; and (b) our experiments, including the one under discussion, show that the faster the flow rates, the greater the *negative* effect on descent detection. The effect of adaptation on the ability to detect loss in altitude, therefore, would be to *improve* sensitivity, since a deleterious influence is decreasing over time. When the level of difficulty is intermediate and descent detection is *relatively* sensitive to this influence, the effect of adaptation is

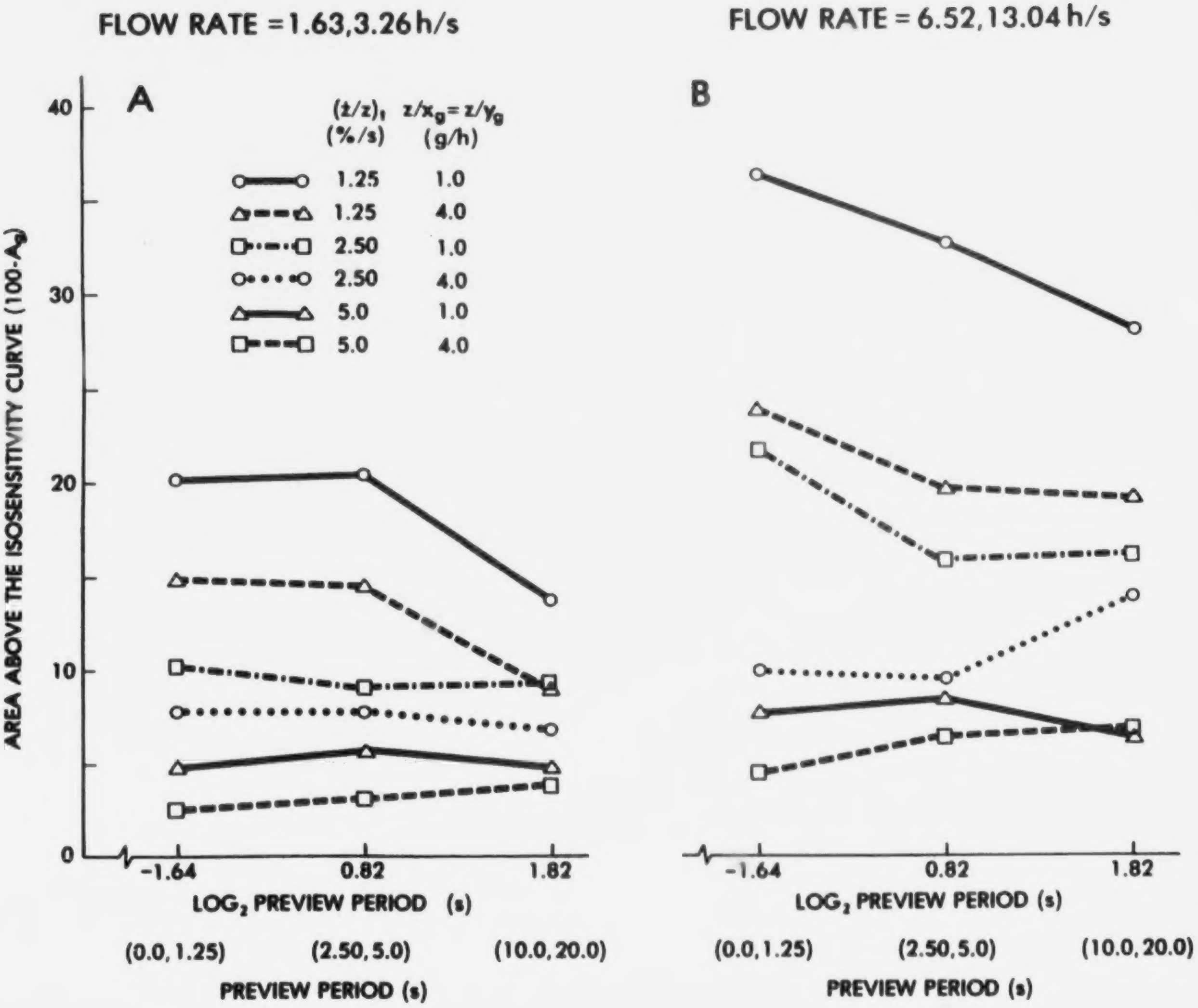

Figure II-5. Area above the isosensitivity curve (100-A_g) as a function of combined pairs of preview periods, fractional loss in altitude ($\dot{z}/z$), and optical density ($z/x_g = z/y_g$), pooled over flow rate values of A, 1.63 and 3.26 h/s and B, 6.52 and 13.04 h/s (288 observations per point).

complete by 2.5 to 5/.0 s for higher flow rates; for lower flow rates, adaptation does not begin to show an effect until 10 to 20 s. When difficulty is highest, the ability to detect loss in altitude is very sensitive to the influence of adaptation, and improvement is seen over the entire range of preview durations. By contrast, detectibility is insensitive to the influence of adaptation when the difficulty level is low. This coincides with our general finding that variables often have little or no influence when detection is easy, but large effects when it is difficult. An examination of Figure II-4 in the context of adaptation provides an explanation for the effect of difficulty: The more difficult it is to detect loss in altitude, the longer the observation time. The longer the observation time, the greater the positive effect of adaptation.

Conclusions

The study of preview effects demonstrated that sensitivity to a functional self-motion variable is modifiable as a function of prior experience, which, in this case, results in adaptation. This converges with recent evidence that various types of training can also reduce the interfering effect of forward speed on the detection of loss in altitude (Hettinger, 1987; Hettinger & Owen, 1985).

The present results confirmed an earlier finding (Hettinger et al., 1985) that a density of 4 g/h is better for descent detection than 1 g/h. This has implications for simulation since higher density is often more expensive to produce and, in the case of computer-generated imagery, may also increase the lag required for perspective transformation of a scene. If, as the results of density studies indicate, there is an optimal level for a given maneuver, then the current drive toward greater detail realism may be tempered somewhat. Greater density is generally associated with higher cost and greater delays in scene computation. It is possible that the dense texturing of highly detailed, realistic scenes may make perception and control more difficult, as should also be the case when scene elements are too sparsely distributed.

Why optical density optimizes is an open question. Spatial frequency sensitivity may be part of the answer, but optical variables linked to density (e.g., edge rate ($\dot{x}/x_g$) and change in density with change in altitude ($\dot{z}/x_g$) and ($z/\dot{y}_g$)) may also play a role. It is likely that sensitivity to loss in altitude optimizes on the lateral dimension (y_g), which determines the perspective "splay" angle. Sensitivity to change in speed is likely to optimize on the forward dimension (x_g), since edge-rate acceleration ($\ddot{x}/\dot{x}_g$) is the most salient information for detecting change in speed (Owen et al., 1984). If so, distances between ground elements both parallel to and perpendicular to the direction of travel can be optimized for two different maneuvers at the same time.

The results are of theoretical significance because they indicate that in understanding self-motion perception, the reciprocity of the perceiver and the nature of the event perceived must be considered as a unit. The information available to support perception and the influence of prior stimulation on the perceptual system interact in systematic ways. These kinds of results support the need for developing a psychophysics of prior experience (cf. Owen, 1978).

The results also have methodological significance in that future studies of self motion must take into account the complex interaction among preview duration and optical variables when assessing sensitivity to a functional event variable. Choosing one level of preview duration (including no preview at all) will differentially affect sensitivity to different levels of the functional variable. This also holds for studies with the goal of training an individual to attend to functional optical variables. Finally, the results are of practical, applied interest. An effect of preview duration may be particularly important in the low-altitude, high-speed environment where flow rates are high and pilots must make decisions about adjustments in speed and direction quickly. To optimize sensitivity after breaking out of cloud cover or cross-checking instruments, a pilot needs to know how much time should be spent sampling the flow pattern before initiating a control action.

Showing that sensitivity is influenced by a variety of optical and event-duration variables is only part of the necessary account, however. The next two experiments (Owen & Wolpert, 1987; Zaff & Owen, 1987) extended this approach to the active control of these variables.

APPENDIX II-A: INVENTORY OF EVENT AND PERFORMANCE VARIABLES

Table II-A-1. Inventory of Event and Performance Variables[a]

Event Number	1 $(\frac{\dot{z}}{z})_t$	2 $(\frac{\dot{s}}{z})_t$	3 $(\frac{\dot{z}}{\dot{x}})_t$	4 $(\frac{\dot{x}}{x_g})_0$	5 $(\frac{\dot{z}}{x_g})_0$	6 $(\frac{z}{x_g})_0$	7 $\dot{s}_0$	8 $\dot{z}_0$	9 x_g	10 %Err	11 $\overline{100\text{-}A_g}$	12 $\overline{RT_c}$	13 $\overline{Conf}$
1	0	1.6	0	1.6	0	1	23.2	0	14.20	22.6		6.98	2.11
2	0	1.6	0	6.5	0	4	23.2	0	3.55	14.5		6.29	2.36
3	0	3.3	0	3.3	0	1	46.3	0	14.20	21.2		6.57	2.21
4	0	3.3	0	13.0	0	4	46.3	0	3.55	9.3		6.01	2.43
5	0	6.5	0	6.5	0	1	92.6	0	14.20	15.9		6.12	2.33
6	0	6.5	0	26.1	0	4	92.6	0	3.55	10.0		5.60	2.47
7	0	13.0	0	13.0	0	1	185.3	0	14.20	16.8		5.81	2.37
8	0	13.0	0	52.2	0	4	185.3	0	3.55	9.1		5.27	2.50
9	0	19.6	0	19.6	0	1	277.9	0	14.20				
10	0	19.6	0	78.3	0	4	277.9	0	3.55				
11	0	26.1	0	26.1	0	1	370.5	0	14.20	14.2		5.19	2.53
12	0	26.1	0	104.4	0	4	370.5	0	3.55	9.6		4.86	2.56
13	1.25	1.6	.77	1.6	.013	1	23.2	.178	14.20	19.1	16.1	5.81	5.27
14	1.25	1.6	.77	6.5	.050	4	23.2	.178	3.55	22.2	12.1	5.57	5.28
15	1.25	3.3	.38	3.3	.013	1	46.3	.178	14.20	29.2	20.5	5.36	5.32
16	1.25	3.3	.38	13.0	.050	4	46.3	.178	3.55	27.1	13.1	5.46	5.35
17	1.25	6.5	.19	6.5	.013	1	92.6	.178	14.20	46.9	27.8	6.29	5.20
18	1.25	6.5	.19	26.1	.050	4	92.6	.178	3.55	38.9	19.9	5.20	5.28
19	1.25	13.0	.10	13.0	.013	1	185.3	.178	14.20	61.5	37.1	6.44	5.25
20	1.25	13.0	.10	52.2	.050	4	185.3	.178	3.55	40.3	21.9	5.40	5.41
21	1.25	19.6	.06	19.6	.013	1	277.9	.178	14.20				

Table II-A-1 (Continued)

Event Number	1 $(\frac{\dot{z}}{z})_t$	2 $(\frac{\dot{s}}{z})_t$	3 $(\frac{\dot{z}}{\dot{x}})_t$	4 $(\frac{\dot{x}}{x_g})_0$	5 $(\frac{\dot{z}}{x_g})_0$	6 $(\frac{z}{x_g})_0$	7 $\dot{s}_0$	8 $\dot{z}_0$	9 x_g	10 %Err	11 $\overline{100-A_g}$	12 $\overline{RT_c}$	13 $\overline{Conf}$
22	1.25	19.6	.06	78.3	.050	4	277.9	.178	3.55				
23	1.25	26.1	.048	26.1	.013	1	370.5	.178	14.20	62.8	32.2	6.10	5.32
24	1.25	26.1	.048	104.4	.050	4	370.5	.178	3.55	37.2	20.5	5.70	5.33
25	2.50	1.6	1.50	1.6	.025	1	23.2	.355	14.2	6.6	7.5	4.80	5.53
26	2.50	1.6	1.54	6.5	.100	4	23.2	.355	3.55	7.3	5.7	4.56	5.61
27	2.50	3.3	.767	3.3	.025	1	46.3	.355	14.20	16.0	11.7	4.91	5.43
28	2.50	3.3	.767	13.0	.100	4	46.3	.355	3.55	18.1	9.3	5.14	5.42
29	2.50	6.5	.384	6.5	.025	1	92.6	.355	14.20	24.7	15.7	5.29	5.35
30	2.50	6.5	.384	26.1	.100	4	92.6	.355	3.55	16.3	9.9	4.64	5.48
31	2.50	13.0	.192	13.0	.025	1	185.3	.355	14.20	3.1	2.0	5.30	5.34
32	2.50	13.0	.192	52.2	.100	4	185.3	.355	3.55	22.6	12.2	4.47	5.47
33	2.50	19.6	.128	19.6	.025	1	277.9	.355	14.20				
34	2.50	19.6	.128	78.3	.100	4	277.9	.355	3.55				
35	2.50	26.1	.096	26.1	.025	1	370.5	.355	14.20	37.8	20.3	5.49	5.31
36	2.50	26.1	.096	104.4	.100	4	370.5	.355	3.55	19.8	11.5	4.72	5.44
37	5.00	1.6	3.070	1.6	.050	1	23.2	.711	14.20	3.1	4.7	3.51	5.78
38	5.00	1.6	3.070	6.5	.200	4	23.2	.711	3.55	3.8	4.1	3.68	5.80
39	5.00	3.2	1.540	3.3	.050	1	46.3	.711	14.20	3.8	5.5	3.75	5.79
40	5.00	3.3	1.540	13.0	.200	4	46.3	.711	3.55	5.2	2.4	4.06	5.74
41	5.00	6.5	.767	6.5	.050	1	92.6	.711	14.20	5.2	6.0	4.32	5.68
42	5.00	6.5	.767	26.1	.200	4	92.6	.711	3.55	8.0	4.9	4.30	5.71
43	5.00	13.0	.384	13.0	.050	1	185.3	.711	14.20	9.70	8.9	4.42	5.65

Table II-A-1 (Concluded)

Event Number	1 $(\frac{\dot{z}}{z})_t$	2 $(\frac{\dot{s}}{z})_t$	3 $(\frac{\dot{z}}{\dot{x}})_t$	4 $(\frac{\dot{x}}{x_g})_0$	5 $(\frac{\dot{z}}{x_g})_0$	6 $(\frac{z}{x_g})_0$	7 $\dot{s}_0$	8 $\dot{z}_0$	9 x_g	10 %Err	11 $\overline{100\text{-}A_g}$	12 $\overline{RT_c}$	13 $\overline{\text{Conf}}$
44	5.00	13.0	.384	52.2	.200	4	185.3	.711	3.55	9.70	7.0	4.22	5.73
45	5.00	19.6	.192	19.6	.050	1	277.9	.711	14.20				
46	5.00	19.6	.192	78.3	.200	4	277.9	.711	3.55				
47	5.00	26.1	.128	26.1	.050	1	370.5	.711	14.20	14.9	10.2	4.42	5.67
48	5.00	26.1	.128	104.4	.200	4	370.5	.711	3.55	12.2	8.3	3.98	5.72

[a] Variables

1 $(\dot{z}/z)_t$ = fractional loss in altitude (percent/s)

2 $(\dot{s}/z)_t$ = global optical flow rate (eyeheights/s)

3 $(\dot{z}/\dot{x})_t$ = path slope (proportion)

4 $(\dot{x}/x_g)_0$ = initial path speed in ground units (edges/s)

5 $(\dot{z}/x_g)_0$ = initial descent rate scaled in ground units (ground units/s)

6 $(z/x_g)_0$ = initial global optical density (ground units/eyeheight)

7 $\dot{s}_0$ = initial path speed (meters/s)

8 $\dot{z}_0$ = initial change in altitude (meters/s)

9 x_g = ground texture size (meters)

10 percent error

11 $\overline{100\text{-}A_g}$ = mean area above isosensitivity curve, where total area = 100

12 $\overline{RT_c}$ = mean reaction time for correct responses (s)

13 $\overline{\text{conf.}}$ = mean confidence rating converted to a 6-point scale (1 = "very certain level" to 6 = "very certain descent").

APPENDIX II-B: INSTRUCTIONS

INSTRUCTIONS

EXPERIMENTER: SEAT THE SUBJECT AND READ:

In this experiment we are interested in investigating how well you can visually detect loss in altitude. You will be shown computer-generated scenes on the screen which represent travel in an airplane over open, flat fields. Your flight path will be level in some scenes, and descending in others. Your task will be to press the lighted button marked "L" if you believe the scene represents constant altitude; i.e., level flight, or the button marked "D" if you detect descent; i.e., loss in altitude.

Sometimes you will see a shimmering flicker of the field along the horizon. Please ignore this effect. It is due to limitations in our equipment.

The specific procedure is as follows:

1. Before the beginning of each event, you will hear a tone. Turn your full attention to the screen at that time.

2. Most events will begin with a period of level travel called the "preview period." After the preview period, you will hear a second tone. After the tone, the event may continue to represent travel at a constant altitude, or it may represent descent. Each event will continue for 10 seconds after the tone. Remember that although you are to observe the entire event, you will be making a judgment only about what occurs after the second tone during the event.

All of the events within a given block of 32 will have the same preview period. Preceding each block, I will tell you how many seconds the preview period will last before the second tone sounds.

3. As soon after the second tone as you can distinguish which type of motion is represented, press the button corresponding to your choice. Indicate your choice as quickly as possible, but without guessing. Please be certain that you press the button only once per event, and do not press either button between events.

4. After you press one of the buttons, please rate your confidence

in the accuracy of your decision by pressing "one" if you are _not certain_, "two" if you are _moderately certain_, or "three" if you are _very certain_ that you made the correct choice.

5. EXPERIMENTER: FIRST TWO TRIALS ONLY: We will begin with two practice events to acquaint you with the procedure. Including the practice events, you will judge a total of 32 events.

Do you have any questions?

6. EXPERIMENTERS: EXPLANATION OF THE PRACTICE SCENES: Scene 1 represents descent, i.e., loss in altitude. Scene 2 represents travel at a constant altitude, i.e., level travel.

7. EXPERIMENTER: READ AT THE BEGINNING OF _BLOCKS 5 AND 11 ONLY_: For this block of 32 trials, there will be no preview period. Therefore, you will hear only one tone. As soon after the tone as you can distinguish which type of event is represented, press the button corresponding to your choice.

FIXATION CONDITION INSTRUCTIONS

EXPERIMENTER: THE INSTRUCTIONS ARE THE SAME AS THE NON-FIXATION CONDITION WITH THE FOLLOWING EXCEPTIONS:

EXPERIMENTER: READ AFTER 1 IN THE NON-FIXATION INSTRUCTIONS.

1a. At this time you will see a number from the group one through nine displayed in the center of the fields. Your task will be to identify the number by saying it out loud to the experimenter. The numbers will not appear after the preview period.

EXPERIMENTER: READ AFTER 7 IN THE INSTRUCTIONS.

7a. In addition, since there is no preview period, there will be no number to report.

APPENDIX II-C: BLOCK ORDER NUMBERS FOR EACH SESSION

Table II-C-1. Block Order Numbers for Each Session

Observers	SESSION			
Group	1	2	3	4
G1	1,2,3	4,5,6	7,8,9	10,11,12
G2	2,12,7	3,4,10	11,5,8	1,6,9
G3	3,11,1	2,6,12	9,4,7	8,10,5
G4	4,6,9	1,12,5	3,7,10	2,8,11
G5	5,4,6	7,10,11	1,12,3	9,2,8
G6	6,8,11	5,7,3	4,2,1	12,9,10
G7	7,9,4	6,11,8	10,1,2	3,5,2
G8	8,5,12	10,3,1	2,9,11	4,7,6
G9	9,10,2	12,8,7	6,11,4	5,1,3
G10	10,3,5	11,1,9	8,6,2	7,12,4
G11	11,7,10	8,9,2	12,3,5	6,4,1
G12	12,1,8	9,2,4	5,10,6	11,3,7

APPENDIX II-D: ANALYSIS OF VARIANCE TABLES

Table II-D-1. Analysis of Variance for Descent Events

Source	df	SS	R^2%	F	p<F
		Error			
Preview period (P)	5	2.23	.15	2.14	.0654
Fractional loss (Z)	2	139.55	9.40	210.88	.0000
Flow rate (F)	4	51.06	3.44	50.66	.0000
Density (D)	1	6.77	.46	5.08	.0336
P x Order (O)	55	20.29	1.37	1.77	.0049
PZ	10	3.61	.24	3.20	.0007
PF	20	9.00	.61	3.96	.0000
ZF	8	12.45	.84	11.50	.0000
ZD	2	4.57	.31	7.97	.0010
FD	4	8.88	.60	14.41	.0000
PZO	110	17.81	1.20	1.43	.0115
PFZ	40	7.86	.53	1.63	.0088
PZD	10	1.79	.12	2.02	.0317
PFD	20	4.94	.33	2.14	.0030
ZFD	8	3.95	.27	3.92	.0003
PZDO	110	15.15	1.02	1.55	.0026
PZFD	40	7.39	.50	1.65	.0073
Pooled error	8190	1167.11	78.61	____	____
Total	8639	1484.41	100.00	____	____

Table II-D-1 (Continued)

Source	df	SS	R^2%	F	p<F
Reaction Time					
Preview period (P)	5	76.57	1.22	11.32	.0000
Fractional loss (Z)	2	434.67	6.90	179.01	.0000
Flow rate (F)	4	14.56	.23	4.73	.0016
Density (D)	1	14.41	.23	4.67	.0408
PZ	10	7.23	.11	1.99	.0347
PF	20	15.23	.24	2.79	.0001
ZF	8	13.84	.22	6.61	.0000
ZD	2	4.47	.07	3.37	.0428
FD	4	16.19	.26	14.06	.0000
PFD	20	11.82	.19	2.25	.0016
PZF	40	27.69	.44	2.61	.0000
ZF x Order (O)	88	33.76	.54	1.47	.0152
PZFD	40	24.36	.39	2.12	.0000
FDO x Fixation (H)	44	21.74	.35	1.72	.0145
PFDOH	220	72.00	1.14	1.24	.0262
PZFDO	440	136.52	2.17	1.34	.0013
PZFDOH	440	130.14	2.07	1.27	.0013
Pooled Error	7251	5244.15	83.23	____	____
Total	8639	6299.35	100.00	____	____

Table II-D-1 (Concluded)

Source	df	SS	R^2%	F	p<F
		Confidence rating			
Preview period (P)	5	5.38	.13	1.44	.2159
Fractional loss (Z)	2	273.75	6.56	68.96	.0000
Flow rate (F)	4	9.93	.24	8.08	.0000
F x Density (D)	4	4.36	.10	3.26	.0150
F x Fixation (H)	4	3.22	.08	2.62	.0396
ZF	8	12.21	.29	3.70	.0005
FH x Order (O)	44	28.82	.69	2.13	.0011
PFZ	40	25.13	.60	2.12	.0001
PZD	10	7.19	.17	2.13	.0232
PFD	20	9.91	.24	1.96	.0081
PFDOH	220	74.04	1.77	1.33	.0059
Pooled error	8283	3725.44	89.13	___	___
Total	8639	4174.00	100.00	___	___

Table II-D-2. Analysis of Variance for Level Events

Source	df	SS	R^2%	F	p<F
		Error			
Preview period (P)	5	1.00	.09	1.11	.3554
Flow rate (F)	4	4.97	.47	4.79	.0012
Density (D)	1	12.45	1.17	37.82	.0000
Replication (R)	2	12.94	1.22	30.64	.0000
P x Order (O)	55	19.90	1.87	2.01	.0003
PR	10	2.61	.25	2.09	.0242
PFD	20	3.47	.33	2.05	.0044
PRO	110	26.17	2.46	1.91	.0000
PFDO	220	23.41	2.20	1.26	.0147
PFDR	40	6.04	.57	1.67	.0058
Pooled error	8172	950.53	89.37	—	—
Total	8639	1063.49	100.00	—	—
		Reaction time			
Preview period (P)	5	141.76	2.19	17.73	.0000
Flow rate (F)	4	230.99	3.57	102.44	.0000
Density (D)	1	35.46	.55	38.71	.0000
F x Replication (R)	8	6.18	.10	2.87	.0044
F x Order (O)	44	35.96	.56	1.45	.0536
PF	20	14.90	.23	2.92	.0000
PFO	220	71.01	1.10	1.27	.0129

Table II-D-2 (Concluded)

Source	df	SS	R^2%	F	p<F
PFD	20	11.59	.18	2.37	.0007
PFRO	440	135.81	2.10	1.20	.0076
FDRO	88	28.58	.44	1.33	.0419
PFDR	40	14.92	.23	1.53	.0182
Pooled error	7749	5750.50	88.75	____	____
Total	8639	6477.66	100.00	____	____
Confidence rating					
Preview period (P)	5	5.45	.13	1.24	.2911
Flow rate (F)	4	95.39	2.29	32.19	.0000
Density (D)	1	51.96	1.25	33.85	.0000
Replication (R)	2	15.70	.38	8.94	.0003
FD	4	13.79	.33	8.66	.0000
PF x Order (O)	220	74.16	1.78	1.26	.0132
Pooled error	8403	3907.33	93.84	____	____
Total	8639	4163.78	100.00	____	____

Table II-D-3. Analysis of Variance for Area Above the Isosensitivity Curve

Source	df	SS	R^2%	F	p<F
Preview period (P)	5	0.93	.01	2.47	.0344
Flow rate (F)	4	11.85	.18	44.28	.0000
Fractional loss (Z)	2	37.08	.57	217.24	.0000
Density (D)	1	6.39	.10	40.04	.0000
P x Order (O)	55	11.32	.18	2.74	.0000
PF	20	2.01	.03	1.93	.0085
FD	4	1.08	.02	5.17	.0006
PZ	10	1.48	.02	3.84	.0001
FZ	8	2.71	.04	8.17	.0000
DZ	2	2.02	.03	16.58	.0000
PFD	20	1.87	.03	1.80	.0174
PFZ	40	2.40	.04	1.73	.0033
FDZ	8	0.61	.01	1.99	.0475
PFZO	440	18.03	.28	1.18	.0134
PDZO	110	4.47	.07	1.36	.0188
PFDZ	40	2.22	.03	1.69	.0050
Pooled error	7870	6347.58	98.36	____	____
Total	8639	6454.05	100.00	____	____

CHAPTER III

PERCEIVING AND CONTROLLING CHANGES IN THE SPEED OF SELF MOTION

Brian S. Zaff and Dean H. Owen
The Ohio State University

Traditionally, perception has been studied by presenting the "observer" with a "stimulus" and constraining the "responses" to a limited set of alternatives. Constraints are imposed upon the passive observer which prevent any exploratory transaction with the environment. The stimulus, defined in terms of features, cues, and elements, is carefully controlled; and the responses are frequently limited to binary decisions and magnitude estimation judgments. With precise controls over stimulation, the sensitivity to isolated variables can be assessed, and lawful relationships between the stimulus and the response can be obtained (Owen & Warren, 1982). When perceiving is construed as the passive registration of points of stimulation rather than the active exploration of the environment leading to the generation of information, the information available in stimulation is often considered inadequate to satisfactorily constrain the intentional behaviors of an individual (Epstein, 1978, 1982; Epstein & Cody, 1980; Rock, 1968). Perceptual capabilities, when taken in this way, require some sort of mediating structure to be rendered meaningful.

However, rather than presuming an inadequate amount of information, the ecological approach to perception operates under the assumption that in a normal environment there is always more information available to be discovered by an active perceiver.

In an analysis of the information available to the individual, it is imperative to maintain a perspective that considers the functional importance of the information for the individual in question. In order to survive in the environment, an individual must have information which will guide life-sustaining activities in ways appropriate to the surroundings. Taken in this sense, information can be understood as the correspondence between environmental properties, as they relate to the individual, and the energy medium as patterned by those properties (Gibson, 1958, 1966, 1979).

Turvey and Kugler (1984), following Gibson, described information for visual perception as optical structures generated in a lawful way by environmental structures and by the activity of the individual, both in terms of the movement of the body relative to the environment and structures in the environment relative to each other. Thus, the information in stimulation is specific not only to what there is in the environment but also to the individual and the relationship that exists between the individual and the environment. Information cannot be divorced from the relationship that exists between the perceiver and what there is to be perceived.

One of the fundamental tenets of the ecological approach to perception is the principle of person-environment mutuality (Gibson, 1979), and the perception-action cycle is a way of describing this reciprocal relationship between the individual and the environment (Owen, 1987b). An individual's perception of the environment provides control constraints for action in the environment, and an individual's actions provide constraints on perception of the environment (Shaw & Alley, 1985). From the perspective of the perception-action cycle, sensitivity to the information specifying the individual's relationship to the surrounding surfaces can be viewed in terms of the coordination between perception and action. In the performance of controlled activities, the coordination of those activities to the surrounding layout of environmental surfaces requires that the information specifying the layout of surfaces and the relationship of the perceiver to those surfaces be effectively utilized during the task. Ideally, the selection of information from an ongoing event and the utility of that information will coincide.

Central to the ecological approach is the idea that information refers to physical states of affairs that are specific to the control and coordination required of activity (Gibson, 1958; Owen, 1987b; Turvey

& Carello, 1981). According to Turvey and Kugler (1984), the requirements for information useful for the guidance of life-sustaining activities can be found in properties of structured patterns of energy relating the person to the environment. The layout of surfaces in the environment is specified by the pattern of structured light that is reflected from environmental surfaces and converges at every point in the medium. Gibson (1958) termed this converging pattern of differential reflectance that is projected to the place of observation the ambient optic array. A transformation in the pattern of the optic array specifying an event not only specifies the relationship among the layout of surfaces in the environment, but also the relationship of the perceiver to the layout of surfaces. As the observation place of a moving individual changes, a continuous family of optical transformations become available to the mobile eye. Gibson, Olum and Rosenblatt (1955) termed the projection of the environment during movement along a path of observation "the flow pattern of the optic array." A global transformation of the optic array specifies self motion, and the specific characteristics of the optical flow pattern specify the kinematics of the movement.

Kinematics refers to the description of motion in geometrical terms, including such characteristics as displacement, velocity, and acceleration. Information about the kinematics of self motion is available in the evolving structure of the patterned energy as the person moves through the surroundings generating information about self motion relative to the layout of the environment. Forward motion relative to the surroundings will lawfully generate an expanding optical flow pattern globally defined over the entire optic array to the point of observation.

In order to understand the perception-action cycle, it is necessary to examine both the individual's sensitivity to the available stimulation and how the individual controls self motion by controlling the variables of optical stimulation. This level of understanding cannot be achieved using a reactive paradigm in which perception is constrained using the passive techniques of traditional psychophysics (Owen & Warren, 1982; Warren & McMillan, 1984). A study in which the test trial begins with presentation of a "stimulus" and ends when the "response" is initiated examines only half of the perception-action cycle. To understand how the individual's actions affect what is subsequently perceived both in terms of how the individual picks up information to guide actions and how the actions make additional information available, an interactive paradigm must be employed (Owen & Warren, 1982).

The task of controlling self locomotion through the environment can provide an instructive forum for an investigation of the perception-action cycle. According to Owen (1987b), the cyclic concept is based on the assumption that perception and action are interrelated, with perception guiding exploratory and performatory actions, and action making available additional information for the perceiver. Since the structure of stimulation is specific to the structure of the environment and the individual's relationship to it, controlling stimulation effectively will result in the intended relationship between the perceiver and the environment. The individual can repeatedly loop through the perception-action cycle until the task is successfully completed or until some constraint is reached. In order to understand the perception-action cycle in general, and how it functions within the task of locomotion in particular, it is first necessary to mathematically isolate the potential sources of information which are useful for the task.

Information for Self Motion

Gibson et al. (1955) performed a series of mathematical analyses of the optical information available during self motion in which the relationship between optical information available in stimulation and the specific layout of the environment was defined. Lee (1980) demonstrated that size, distance, and the individual's relationship to environmental surfaces could be specified in terms that are intrinsic to the relationship between the perceiver and what there is to be perceived.

Although several potential sources of visual information for self motion have been mathematically isolated (Gibson et al., 1955; Lee 1976, 1980; Warren, 1982), the existence of an invariant structure in the optic array does not ensure that that potential source of information will have psychological relevance for a given individual performing a particular task. It is not at all inappropriate from an ecological perspective to regard the psychologically relevant sources of visual information as possibly distinct from the potential sources of information. Any number of potential sources of information may prove irrelevant for the task at hand, but evidence of frequently successful performance of the task would indicate that the individual possesses a sensitivity to at least one source of information. It is therefore an empirical question as to which optical invariants or potential sources of information are actually informative.

Since the ecological approach has described information as pointing in two directions, being both informative to someone and about something (Owen, 1987a), it becomes necessary to describe potential information both in terms of what it is informative about and what the individual does with that information. Owen (1985) has suggested a method of classifying information on the basis of both what the individual does with the information and whether that aspect of stimulation is relevant to effective performance of the intended task. The system of classification proposed involves formulating a distinction between functional and contextual variables. The concept of a functional variable preserves the fundamental tenet of person-environment mutuality, as neither the individual nor the environment alone determines the functional value of some event parameter. An event-specific variable is considered functional only when it is both (a) relevant to the performance of the intended task and (b) the aspect of stimulation to which the individual is attuned. The functional variable is an event-specific variable to which the individual is attuned and is the specific aspect of stimulation that the individual intends to control. It is the nature of the particular environmental conditions upon which the individual operates, relative to the task demands, that determines the relevancy or irrelevancy of the particular aspect of stimulation; and it is the individual who determines the aspect of stimulation to which he or she will attend, and the aspect of stimulation which he or she will attempt to control. The functional variable is relevant to and informative about that which the individual intends to distinguish or control. The functional variable is useful in the performance of the task at hand, and successful control of a functional variable will result in effective performance of that task. If the individual attends to some parameter of stimulation with the intention of making a certain distinction or performing a particular task, and that information is irrelevant for those purposes, then the transaction between the individual and the environment will result in what could be termed a _dysfunctional_ variable (see Table I-1).

The functional variables that have been identified in previous research (Owen et al., 1981; Tobias & Owen, 1984) have the characteristics of being both _relational_, in the sense that the non-arbitrary relationship between perceiver and environment is preserved, and _relative_, in the sense that they are not specific to either absolute optical or event variables. The ambient optic array consists of a nested configuration of texture gradients, sensitivity to which does not depend on the absolute magnitude of that parameter but rather, on the higher-order relationship that exists between the absolute values. This relativistic nature of the functional variable frees the perceiver from the need to know absolute distance, speed, or flow rate in order to be sensitive to changes in speed or direction.

Owen et al. (1981) factorially combined initial speeds and decelerations to produce different levels of fractional change in speed. The results of the study showed that changes in performance were linked with changes in the magnitude of the fractional rate of change. Differing magnitudes of deceleration having identical levels of fractional rate of change, however, had no influence on performance, thereby identifying initial fractional change in flow rate as the functional variable for the task of detecting changes in the rate of self motion.

Contextual variables are also defined in such a way as to preserve the idea of person-environment mutuality. A contextual variable is that aspect of stimulation which is both (a) irrelevant to the performance of a particular task and (b) something to which the individual is _unattuned_. In spite of the fact that the information is irrelevant for the performance of the task and the individual does not attend to it, contextual variables are often found to influence the individual's sensitivity to some relevant aspect of stimulation, but in a different way than do functional variables. However, when the individual is not attuned to information that is relevant to the performance of the task, potentially useful information remains unused and possible differentiations are not made, as the subtle distinguishing characteristics of an event are not apprehended. Under such conditions, the parameter of stimulation would be considered *nonfunctional*.

Owen (1985) pointed out that the contextual variable is sometimes essential to the perception of the event. There must, for example, be some optical discontinuity in order to manifest flow-pattern changes; for in the case of unstructured ambient light (e.g., a "white-out"), an environment is not specified and no information about the environment is available. Some contextual variables can affect functional sensitivity without being essential to perception of the event; but regardless of whether or not the contextual variable is essential, some contextual variables have been shown to have an effect on performance. No a priori means exist for determining whether a contextual variable will influence performance. The distinction is an empirical one.

A reactive paradigm, in which observers are required to distinguish between two possible self-motion events, can be useful for making an operational distinction between functional and contextual variables on the basis of the psychophysical function produced by each as an independent variable. The functional variables have an asymptotic effect on performance. Between the asymptotes, increasing the magnitude of a functional variable results in increasingly better performance, and decreasing the magnitude results in increasingly poorer performance. Contextual variables tend to display either flat functions when they do not influence sensitivity to the functional variable at all, or optimizing functions, in which very low *or* very high levels of the variable result in poorer performance when they do influence sensitivity to the functional variable. As examples of contextual variables influencing sensitivity, Tobias and Owen (1984) demonstrated, for the task of detecting changes in the rate of self motion, that either very low or very high flow rates or optical densities resulted in poorer performance than did values in the middle range.

Interactive Research

Since successful control of self motion through the environment requires sensitivity to the variables of stimulation, studying sensitivity to these variables of stimulation in a reactive setting can be informative. However, by examining performance of a particular control task, it becomes possible to assess the nature of the perception-action cycle and to assess how the individual is able to effectively gain tighter control over the perception-action cycle. For this purpose, an interactive paradigm, which permits the individual's actions to affect the available information, must be employed. An interactive methodology requires the participant to perform a particular task, such as maintaining constant direction and/or speed of travel. The individual's control adjustments can be construed as an attempt to achieve a particular perceptual consequence as they control simulation. The parameters of stimulation become the dependent variables, rather than independent variables as in the reactive paradigm. Zacharias and Young (1981) gave subjects control over stimulation, in an effort to determine their sensitivity to various sources of information specifying self motion. The experiment examined the influence of high- and low-frequency yaw-axis perturbations which were presented both visually and vestibularly to assess the independent contribution of each subsystem to the control of self motion. The participants were seated on a rotating motion-base platform in front of a horizontal grating pattern and were instructed to maintain a constant "subjective" position by controlling the drift of the grating pattern. The participants' compensatory behavior, which was generated as they attempted to maintain a fixed position in space during the yaw-axis perturbations, was used as an index of sensitivity.

Warren and McMillan (1984) also employed an interactive paradigm to examine the combined influences of both optical and control variables on the ability of the participants to maintain a constant simulated altitude. However, because of the complex nature of the relatively violent quasi-random vertical perturbations in stimulation, which were extrinsic to the participants' control, the analyses of the participants' performance both in terms of the characteristics of the stimulation they were controlling and overall accuracy was difficult to interpret.

In light of the largely exploratory nature of the interactive paradigm in this stage of its evolution, it has been deemed prudent to begin this inquiry into the nature of the perception-action cycle with a very simple case. Because of the knowledge base that has been accumulated concerning the perceiver's sensitivity to optical variables specifying changes in the rate of self motion, the present study will focus on the active control of the speed rate of self motion.

The use of an interactive paradigm will also provide an opportunity to investigate improvements in the skill of controlling information in stimulation (Owen, 1987a; Owen & Warren, 1982). When the individual is given control over stimulation, as in the case of visually guided self motion, it becomes possible for the person to see when performance is in error and make adaptive adjustments during the ongoing event or make a change in strategy between events (Owen, 1987a).

By using traditional methods of assessing the observer's sensitivity that do not permit direct control over stimulation and the information available, investigators have shown only moderate improvements in performance with practice (Hettinger & Owen, 1985). Hettinger and Owen found that with judgement tasks designed to assess sensitivity to changes in altitude, providing the subjects with either prior knowledge about the type of transformation to be encountered, or verbal feedback concerning the accuracy of their response, resulted in an approximately 20% improvement in performance. Giving the participants control over stimulation is expected to result in substantially larger improvements in performance.

Held (1965) found that giving animals control over stimulation was crucial to the development of coordination between perception and action. Thus, giving the subjects control over stimulation in the present context is also likely to result in substantial improvements in sensitivity to the functional variables and in the skill needed to control these variables. Having control over the information in stimulation should facilitate an education of attention to relevant and irrelevant sources of information for the performance of the task of controlling the rate of self motion.

Introduction to the Present Experiment

Flow rate. Information for the visual system in general has been defined as the optical structure generated in a lawful way by environmental structures and the relationship of the perceiver to the environment (Gibson, 1958, 1966, 1979). Information for self motion in particular is optically specified as a global transformation in the optic array. Following Gibson et al. (1955), Warren (1982) defined the change in optical position ($\dot{O}P$) of a ground-texture element as:

$$\dot{O}P = (\dot{s}/z)\ \sin^2 EL\ ((\sin^2 AZ\ \csc^2 EL + \cos^2 AZ)\ \cos^2 PA + \cot^2 EL\ \sin^2 PA - 2\cos AZ\ \cot EL\ \sin PA\ \cos PA)^{1/2}$$

where AZ = the azimuth or angular position of a point along the horizon, EL = the elevation or angular position of a point above or below the horizon, and PA = path angle or the angular separation of the aim point and the horizon. The multiplier ($\dot{s}/z$) is termed *global optical flow rate*, since it is a scalar on the motion of all texture elements in the optic array. The global transformation or global optical flow rate can, therefore, be defined as the individual's speed along a path of locomotion ($\dot{s}$) scaled in eyeheights (z) and is thus a function of both the path speed and altitude. When the path of locomotion is level with respect to the surface, the path speed ($\dot{s}$) becomes equal to the forward speed ($\dot{x}$) and global optical flow rate can be defined as ($\dot{x}/z$). A change in the rate of self motion ($\ddot{x}$) can be optically specified either in terms of global optical flow acceleration ($\ddot{x}/z$) or as a ratio of flow acceleration to flow rate (i.e., a fractional rate of change in speed and flow rate ($\ddot{x}/\dot{x}$)).

A systematic empirical examination of the potential sources of information for the detection of change in the rate of self motion led Owen et al. (1981) and Tobias and Owen (1984) to conclude that the fractional rate of change in flow rate ($\ddot{x}/\dot{x}$) was the functional variable specifying a change in the rate of self motion. Performance, as indexed in terms of both accuracy and speed of detecting changes in the rate of self motion, improved significantly as the initial fractional rate of change in speed assumed higher values. Varying the level of initial flow acceleration, while holding the fractional rate of change constant, had little effect on performance.

Edge rate. The existence of optical discontinuities produced by the texture pattern on environmental surfaces is necessary for optical manifestation of a flow pattern. However, the optical flow rate in eyeheights per second is invariant with respect to the particular texture distribution on an environmental surface. The distance between texture elements on the surface produces an angular difference in the optic array between the optical discontinuities. Movement of the individual relative to texture elements at a constant distance in the environment produces an edge rate, which is defined environmentally as the number of distinct texture elements traversed per unit time and optically as the number of optical margins, corresponding to the texture elements, flowing past an arbitrarily defined optical locus per unit time (Warren et al., 1982). If the edges created by surface discontinuities are regularly or stochastically regularly spaced, the edge rate is potentially informative about the rate of self motion. Under such conditions, this information, scaled in terms of ground-texture elements, is invariant with respect to differences or changes in altitude, but does vary with any structural change in the spacing of ground-texture elements that occur perpendicular to the direction of travel (Owen et al., 1984).

Perceptual effectiveness. Under conditions of constant altitude and regularly spaced terrain, flow rate and edge rate are linked to one another because they differ from ground speed and from each other only by scaling factors. Thus, for a terrestrial animal with a nearly constant eyeheight, or a pilot flying at a constant altitude, neither flow rate nor edge rate can be considered privileged with regard to unequivocal specification of the speed of self motion. Although both flow rate and edge rate are redundant optical specifiers of self motion under such conditions, neither could be considered relevant information for the task of detecting a change in the rate of self motion, as both are of first-derivative order with respect to time. Thus, they cannot be informative about change in speed, which is a second-order derivative with respect to time. However, from prior studies (Owen et al., 1984;

Warren et al., 1982), it is known that both the initial value of global optical flow rate and the initial value of edge rate influence sensitivity to the perception of self acceleration. It was shown that as the values of both initial flow and initial edge rate increased, the frequency of "acceleration" reports increased. It also has been shown (Tobias & Owen, 1984) that initial flow rate and/or initial edge rate (as the variables were linked, in this case, rather than being factorially crossed) influenced sensitivity to decelerating self motion. Very low or high values of these optical variables resulted in poorer performance than did values in the midrange.

Although both the Owen et al., (1984) study and the Tobias and Owen (1984) study demonstrated that the initial value of global optical flow rate influences sensitivity to changes in egospeed, the characteristics of the influence are different in each case. Owen et al. (1984) found that sensitivity to egospeed acceleration increased with an increasing initial value of flow rate, whereas in the Tobias and Owen study, the function optimized over a similar range of values for initial flow rate. There is an obvious difference between the two experiments in that one involved accelerating self motion and the other involved decelerating self motion. When the rate of change in speed ($\ddot{x}$) is held constant, accelerating self motion will result in an exponentially decreasing fractional change in speed ($\ddot{x}/\dot{x}$) over time, and decelerating self motion will result in an exponentially increasing fractional change in speed over time (see Figure 1, p. 12, in Tobias & Owen, 1984). To the extent that the individual is sensitive to fractional change in self motion (Owen et al., 1981), a loss in speed will become easier to detect over time, and a gain in speed will become more difficult to detect. In addition to the difference in sensitivity resulting from the direction of the change, the optical difference that occurs over time may account for the apparent task-dependent difference in the influences of initial flow rate on sensitivity to accelerating or decelerating self motion.

Purpose and predictions. When perceiving is construed as the acquisition of information useful for guidance of controlled behavior in a way which is appropriate to the surrounding layout of environmental surfaces, it becomes possible to use an individual's actions as an indication of what he or she is perceiving. Thus, it is reasonable to assume that the factors influencing an individual's sensitivity to an optical event will also influence that individual's ability to control the optical transformation when he or she changes from the role of an observer to the role of a performer. It is therefore possible to extract a dependent measure from an examination of the actions which are necessary in the successful performance of some task (Owen & Warren, 1982; Warren & McMillan, 1984). Using an interactive technique, the present investigation will focus on the influence that initial global optical flow rate, initial edge rate, and initial fractional change in both have on an individual's ability to detect and control changes in the kinematics of self motion.

The present investigation will also attempt to clarify some of the issues raised in prior studies, by assessing the separate contributions of edge rate and flow rate to the perception of both accelerating and decelerating rates of self motion. The relative perceptual effectiveness of various optic array configurations for the perception of changes in the rate of self motion will be assessed by testing participants with a factorial crossing of edge rate, flow rate, and fractional rate of change in both, and noting the relative influence that each factor has on the participants' ability to detect and control the rate of simulated self motion.

To the extent that the task of detecting changes in the speed of self motion using an interactive methodology is equivalent to the task of detecting changes in the speed of self motion which was employed in the judgment studies, similar results are expected. Namely, increasing the level of fractional change in speed is expected to result in improvements in the ability of the subjects to detect changes in speed. Initial global optical flow rate and initial edge rate, although irrelevant sources of information for the task of detecting changes in the speed of self motion, are both expected to have a deleterious influence on sensitivity to functional variables, as observed in previous studies (Owen et al., 1984; Tobias & Owen, 1984).

Arguing from the ecological approach, it is possible to make predictions about both the effect of optical variables on the participants' ability to maintain a constant velocity, and the effects that practice has on performance. First, because it is possible to conceive of action as the control of stimulation until an intended perceptual outcome is achieved (Gibson, 1958), it is possible to predict that the optical variables that affect the participants' ability to detect changes in the speed of self motion will also affect their ability to control those changes. Second, giving the participants control over their own stimulation makes available intrinsic visual feedback obtained simply by perceiving the consequences of their actions. Under such conditions, substantial improvements in performance are to be expected.

Method

Apparatus. The simulated self-motion events were generated by a PDP 11/34 computer and a special-purpose scene generator (see Yoshi, 1980), and displayed via a Sony Model KP-7240 video projection unit. The sampling rate of 30 frames/s for the scene generation matched the scanning rate of the video projector. The observer was seated on an elevated chair 2.43 m in front of the screen and had a viewpoint at the level of the simulated horizon, which was 1.96 m above the floor. The video unit had a screen 1.5 m in width and 1.125 m in height, producing a visual angle of 34.3 deg by 26.1 deg. A Measurement Systems Model 436 isometric or force-sensing control, mounted on a stationary platform directly in front of the subject at a height of 1.2 m, was used to control the change in speed of simulated flight. The force control served as a double-integration controller, such that application of a constant force would result in either a constant acceleration if the force were applied in the direction of simulated travel or a constant deceleration if the force were applied opposite to the direction of travel. The adjustable gain was set to saturate at ± 50.0 m/s^2 with the application of 6.8 kg of force.

Scenes. All events represented level self motion at an altitude (z) of 12, 24, or 48 m over a flat, rectangular island extending 30.72 km parallel to the direction of travel (x dimension) and 456 m perpendicular to the direction of travel (y dimension). The texture blocks representing fields on the island were 6, 12, 24, 48, 96, or 192 m in length (x dimension). The number of edges along the y dimension was fixed at 19, and all texture blocks were 24 m in width. (See Appendix III-A for complete inventory of flight and texture parameters.) Four earth colors (light brown, dark brown, light green, and dark green) were randomly assigned to the texture blocks, with the constraint that no two adjacent texture blocks could have the same color. The area above the horizon was pale blue, and the nontextured area surrounding the island was a medium green.

Owen et al. (1985) found that sensitivity to decelerating self motion was reduced as a result of exposure to a constant speed preview period that lasted for less than 20 s when compared with sensitivity resulting from a 0-s preview period. Sensitivity to decelerating self motion was seen to increase after 20 s, but not to exceed the level of sensitivity observed for a 0-s preview period until the exposure to constant speed reached 40 s. Thus, for the sake of economy in data collection, and to avoid possible confounding effects due to the preview period, a preview period was used in the present experiment. Each trial lasted for 10 s followed by a 5-s inter-trial interval. The test session, consisting of four practice trials and 108 test trials, required 28 min to complete.

Design. The experimental design consisted of two event types representing accelerating and decelerating speed, with three levels of initial fractional rate of change in speed ($\ddot{x}/\dot{x}$ = 6.4, 8.0, and 10.0 %/s) crossed with three levels of initial global optical flow rate ($\dot{x}/z$ = 4.0, 8.0, and 16.0 h/s) and six levels of initial edge rate ($\dot{x}/x_g$ = 1, 2, 4, 8, 16, and 32 edges/s). The levels of initial global optical flow rate, edge rate, fractional rates of change in flow rate, and global optical texture density were selected so that they overlapped with the levels used in the Tobias and Owen (1984) and Owen et al. (1984) experiments in order to facilitate a direct comparison.

The full factorial crossing produced 108 unique events. (See Appendix III-B for a complete inventory of the event variables and performance variables.) A random sequence of events was generated by creating three blocks of 36 trials, with the constraint that no more than three instances of any level of any variable or any event type appeared in succession. Each block contained 18 trials of each event type (accelerating or decelerating), 12 trials from each level of initial flow rate, 12 trials from each level of fractional rate of change, and 6 trials from each level of edge rate. All six possible block sequences were used. In each test session, the participant received four practice trials and three blocks of 36 test trials. The first two practice trials simulated constant speed flight and were designed to allow the participant to become acquainted with the force control and with the system's dynamics. The third and fourth practice trials simulated decelerating and accelerating forward speed, respectively. The practice trials consisted of the midrange values of the optical parameters, selected from among those under investigation in the test events.

Procedure. At the beginning of the first of four test sessions, the participants were read the instructions presented in Appendix III-C. Before each test session, the participant was given four practice trials. The participants were told that every trial would begin at the same speed. They were instructed to maintain a constant speed during the simulated flight, such that as soon as they detected a change in speed, they were to adjust the control by applying an appropriate force in the appropriate direction in order to cancel the computer-initiated change in speed, and then maintain a constant speed for the remainder of the trial. The computer updated the scene and recorded the control output once every 33.3 ms. The participant wore headphones that produced 60 db of white noise during the entire test session. An acoustic "ready" signal was presented prior to the start of each trial, at which time the participant was instructed to turn his full attention to the screen.

Participants. Participants were 45 male undergraduates at The Ohio State University. All participants took part in the experiment in order to fulfill an extra-credit option of an introductory psychology course, and claimed no previous experience in a flight simulator or as a pilot.

Results

A mixed-design analysis of variance was performed on data obtained from 35 of the 45 subjects tested. Since the purpose of the experiment was to assess the influence of a number of optical variables (flow rate, edge rate, and fractional change in both) on the ability to control speed, participants were discarded if they had error rates for direction of response that were at or near chance levels throughout the four test sessions. (See Table III-1 for a summary of error rates for discarded participants.) Two additional participants were discarded because they failed to follow instructions; rather than attempting to cancel the forcing function and maintain a constant velocity, they saturated the control by consistently applying the maximum force possible throughout the trial.

Table III-1

Proportion Error for Deleted Subjects

	Session				
Subject	1	2	3	4	Mean
7	.44	.39	.45	.53	.45
8	.45	.50	.56	.46	.49
12	.37	.46	.42	.45	.43
17	.57	.69	.76	.64	.66
19	.48	.47	.49	.47	.48
23	.65	.69	.63	.68	.66
25	.47	.45	.44	.48	.46
33	.46	.48	.39	.47	.45

The analyses were performed on proportion error, mean reaction time, and slope of the initial control adjustment for all events in the experimental design. In the case of the slopes, an analysis was performed on the absolute magnitude of the slope in order to avoid effects due simply to the direction of response. Because of the characteristically different nature of accelerating and decelerating events, and because of the different sign attached to each performance variable as the subjects attempted to counter a forcing function of the opposite sign, separate analyses for acceleration and deceleration events were performed on the 14 performance measures computed on data from the maintenance phase. The performance variables during the maintenance phase included the mean and standard deviation in velocity, acceleration, flow rate, flow acceleration, edge rate, edge acceleration, and fractional change in speed.

A large number of observations was used in an effort to stabilize the data summary. As a result, many effects of little consequence were statistically significant according to conventional probability criteria. Therefore, it was decided that in order to merit discussion, an independent variable must reach the $\underline{p} \leq .05$ level of significance and be an effect of particular interest or account for at least 1% of total variance. (Complete listings of all effects with $\underline{p} \leq .05$ are presented in Appendix III-D.)

The effect for counterbalance order and several interactions involving this variable were significant, and accounted for more than 1% of the variance in both the mean and standard deviation of several of the performance variables. These effects were apparently due to the poor performance of three participants who were, by chance, all assigned to the same counterbalance group. No other interpretable structure could be attributed to the effects involving order, and these effects merit no further discussion.

The control performance of a practiced participant is illustrated in Figures III-1 and III-2. The force stick was an acceleration controller, and the participant's control of acceleration can be seen plotted against time. Four trials were selected to represent good performance on an acceleration event; good performance on a decelerating event; and two types of characteristically poor performance, one showing constant error and the other showing variable error.

Figure III-3A, showing a segment of performance on an acceleration event, is useful for illustrating some important features of the data: the forcing function, response initiation, the initial correction slope, and the maintenance phase of performance. The dependent measures

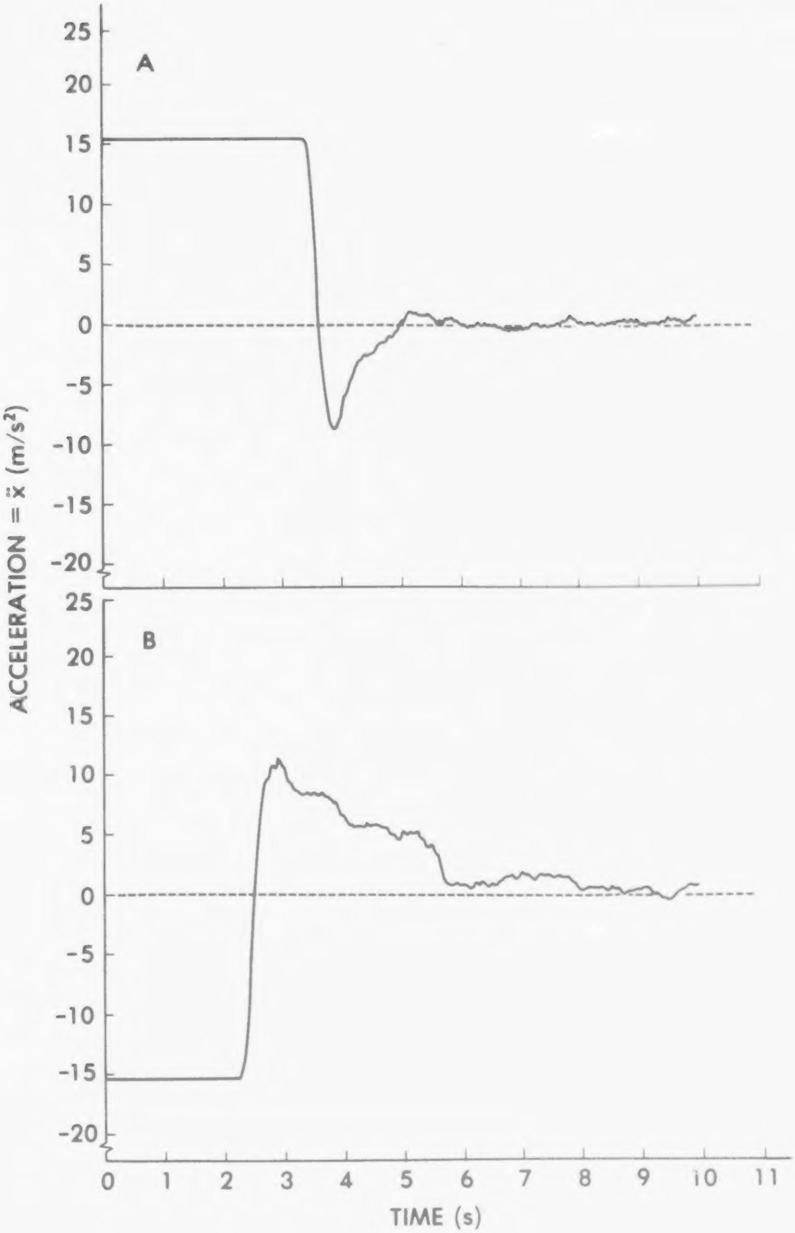

Figure III-1. Acceleration time histories showing good performance by a practiced subject attempting to counter a positive forcing function (A), and a negative forcing function (B), and then maintain a constant rate of self motion.

70

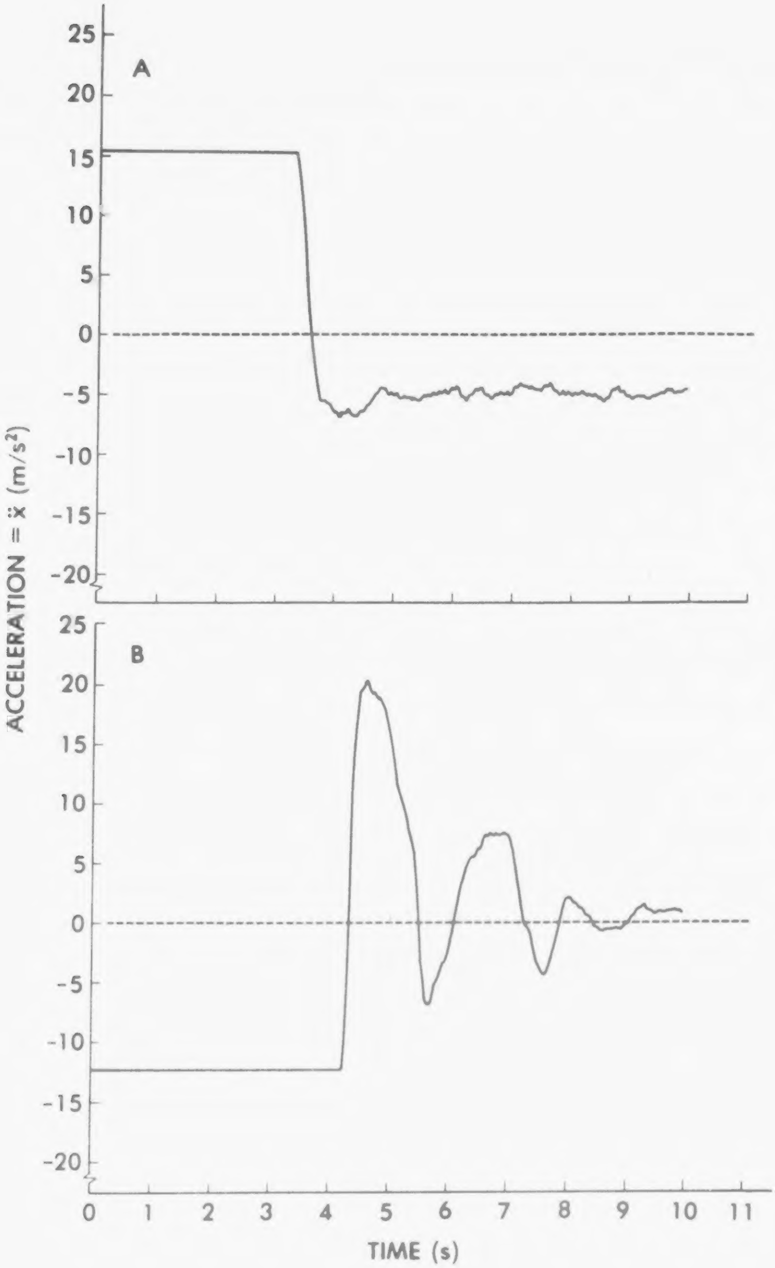

Figure III-2. Acceleration time histories showing constant error for a positive forcing function (A) and variable error for a negative forcing function (B) produced by a practiced subject attempting to maintain a constant rate of self motion.

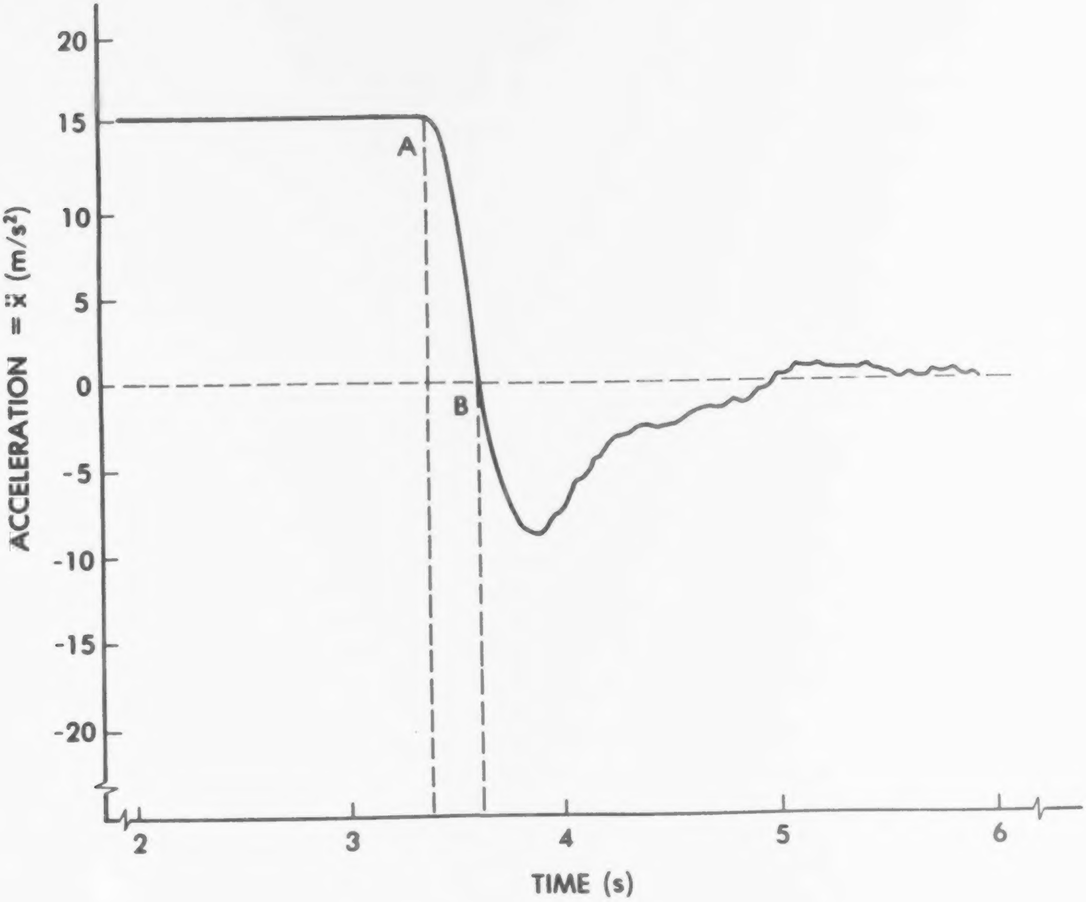

Figure III-3. Segment of acceleration time history showing response initiation phase at point A, initial correction phase between points A and B, and maintenance phase from point B until completion of 10 s events.

examined during the initial response phase of performance were errors in direction of response and reaction time. The initial correction phase or "ramp" of the control action was defined as consisting of the time series from reaction time until the forcing function had been cancelled or until 300 ms had elapsed, whichever occurred first. The 300-ms criterion was used on approximately 32% of the trials. The mean duration of the ramp segment was 238 ms for accelerating events and 190 ms for decelerating events. Each ramp segment was subjected to a linear regression fit, for which the mean R^2 value was 0.90 for both directions. A slope and an intercept were computed for each trial. In addition, 14 other dependent measures of maintenance performance were obtained, including the mean and standard deviation in velocity, acceleration, flow rate, flow acceleration, edge rate, edge acceleration, and fractional rate of change.

Because of the large number of dependent variables, the summary of the results will be organized into three sections. First, the results for response initiation will be reported, followed by the results of the ramp phase of the corrective response, and finally, the results of the maintenance performance (see Figure III-3).

Response Initiation Variables

Error in direction of response. The strongest effect on error rate resulted from an interaction between initial flow rate and direction of change in speed, and accounted for 1.37% of the variance in errors. Figure III-4A shows that for acceleration events, error rate decreases as initial flow rate increases; whereas on deceleration trials, initial flow rate has the opposite effect.

The interaction between initial fractional rate of change and direction is also significant and accounts for 0.11% of the variance in mean error rates. Error rates, as illustrated in Figure III-5A, decreased with higher initial fractional rates of change on acceleration trials. Initial fractional rate of change, however, had very little influence on error rates for deceleration trials.

The effect of number of sessions on error rate was significant, as were three three-way interactions of particular interest. The first interaction involved session, initial flow rate, and direction; the

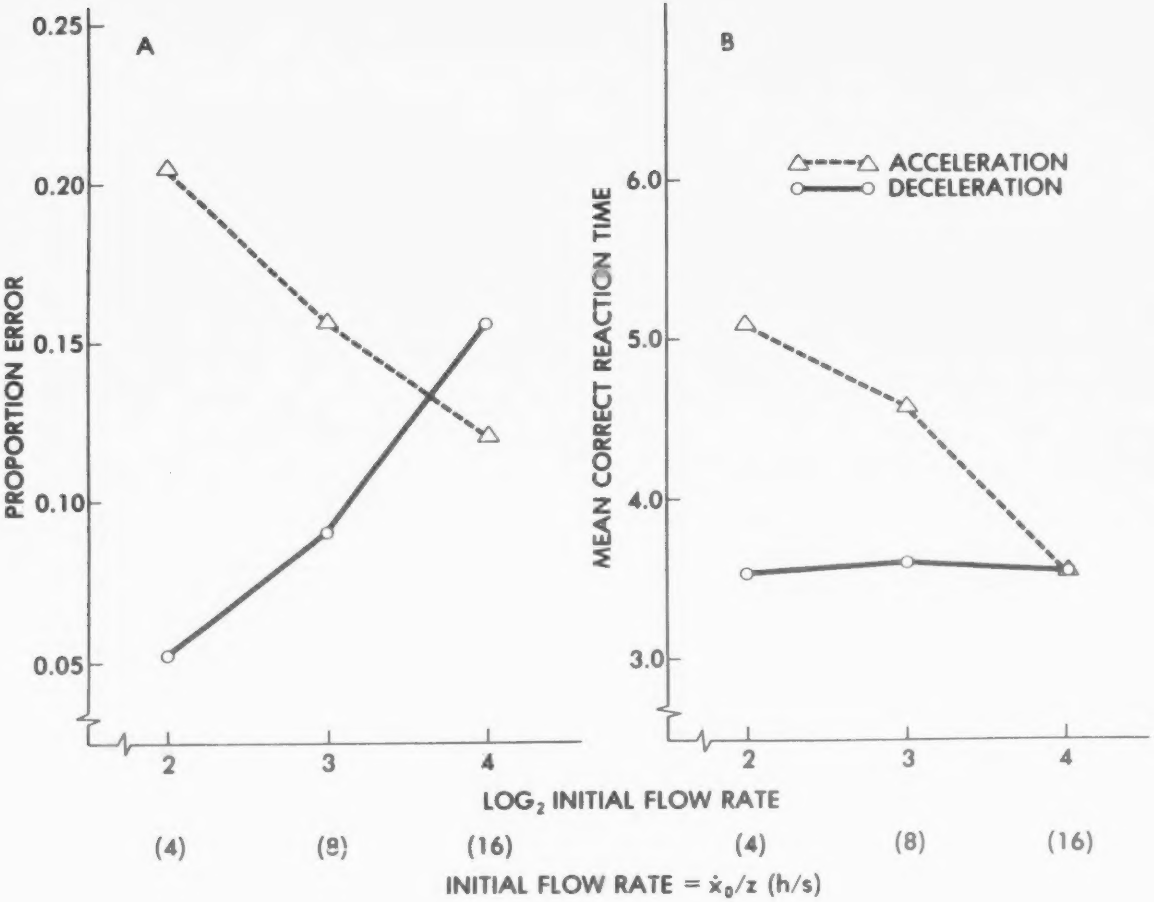

Figure III-4. Proportion error (A) and mean correct reaction time (B) as a function of initial global optical flow rate for events representing accelerating and decelerating self motion.

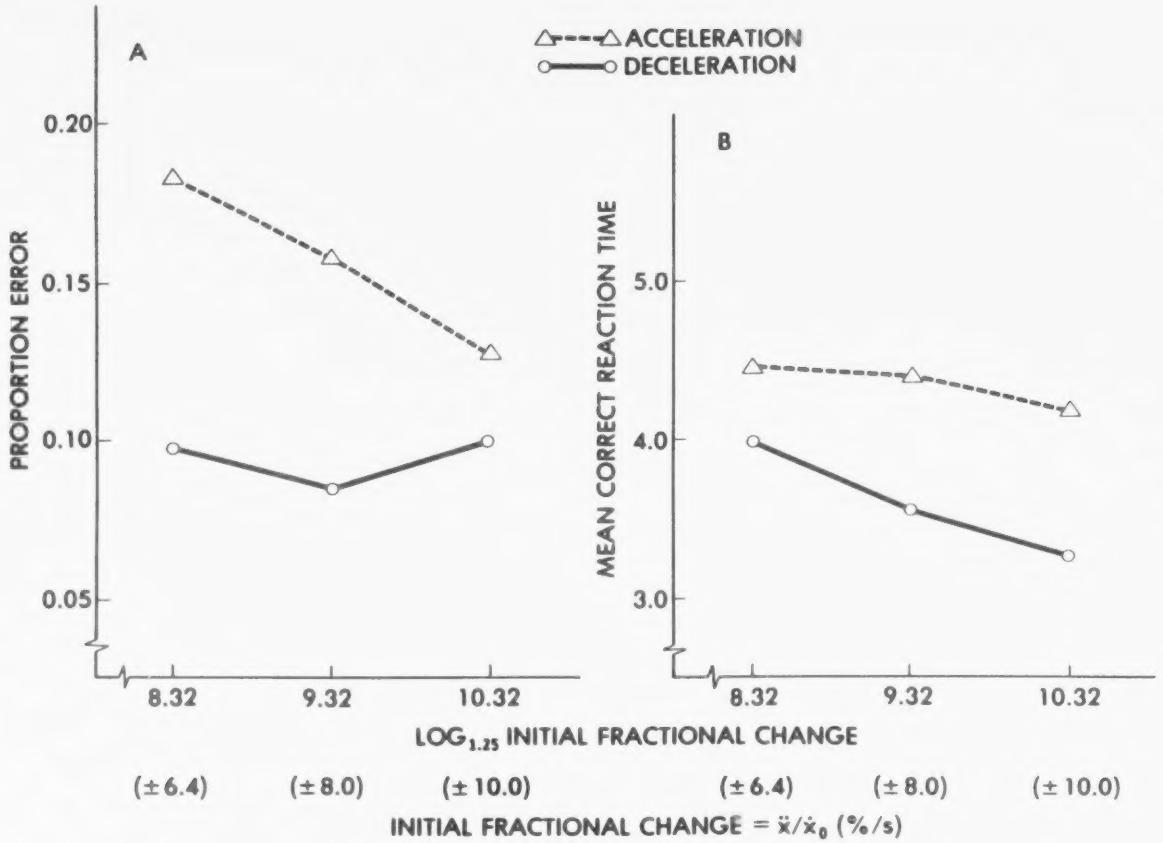

Figure III-5. Proportion error (A) and mean correct reaction time (B) as a function of initial fractional change in speed for events representing accelerating and decelerating self motion.

second involved session, initial edge rate, and direction; and the third involved initial flow rate, initial edge rate, and direction. The effect of session accounted for 0.52% of the variance in errors. Figure III-6 shows that, for decelerating events, the error rate dropped from 16.0% to 7.3% overall, a 54.4% improvement in performance with practice. For accelerating events, the error rate dropped from 17.9% to 13.3% overall, a 25.7% improvement in performance with practice. The three-way interaction among session, initial flow rate, and direction accounted for 0.12% of the variance in mean error rate; and the three-way interaction among session, initial edge rate, and direction accounted for 0.28% of the variance (see Figures III-7A and III-8). Both three-way interactions revealed an appreciable improvement in performance with practice. Error rates generally remained higher for higher values of initial flow and edge rates across sessions, although the magnitude of the difference was greatly reduced with practice. Performance associated with the higher initial flow and edge rates showed the greatest improvement. The three-way interaction among initial flow rate, initial edge rate, and direction, shown in Figure III-9, is also of particular importance, for it reveals the cumulative effect of initial flow and edge rates on error rates. For deceleration events, the combined effects of the highest initial flow and edge rates resulted in five times more errors than the lowest rates. For acceleration events, the interaction between flow rate and edge rate had no discernible structure.

Reaction time. The strongest effect on reaction time was due to level of initial flow rate for accelerating events, which accounted for 2.17% of the variance. Figure III-4B shows that time to detect acceleration became shorter as initial flow rate increased, but reaction time remained essentially unchanged over levels of initial flow rate for decelerating events. The effects of initial fractional change and initial edge rate were also significant, but no interpretable structure could be discerned for the effect of initial edge rate on reaction time. Figure III-5B shows that reaction times dropped as initial fractional change increased for both accelerating and decelerating events, accounting for 0.70% of the variance in reaction times.

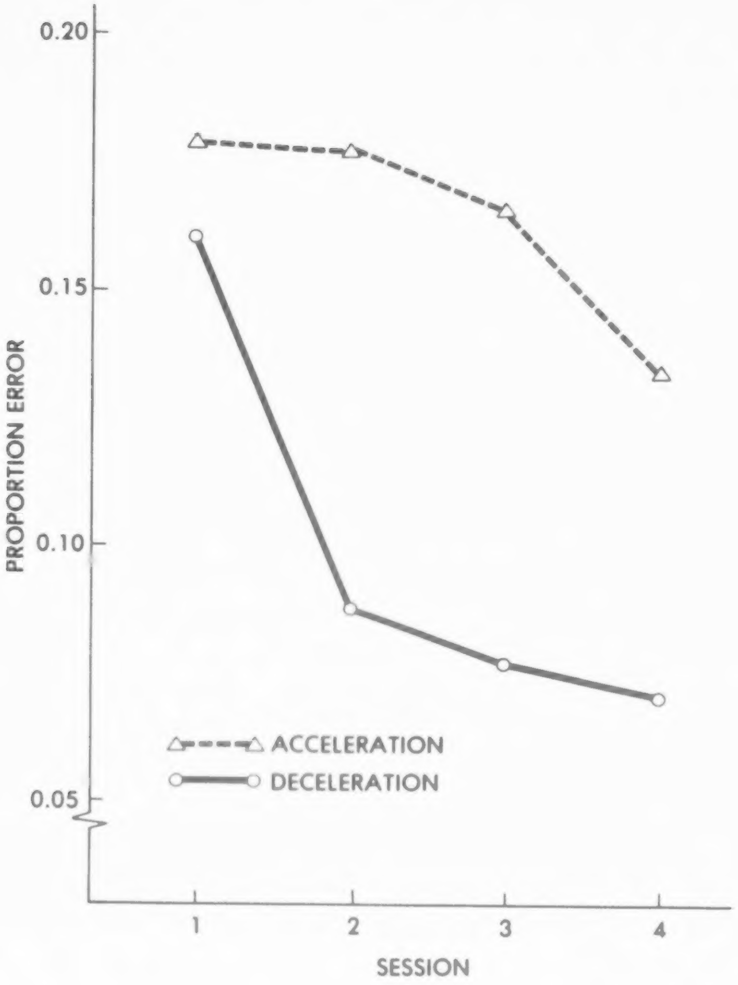

Figure III-6. Proportion error as a function of session for events representing accelerating and decelerating self motion.

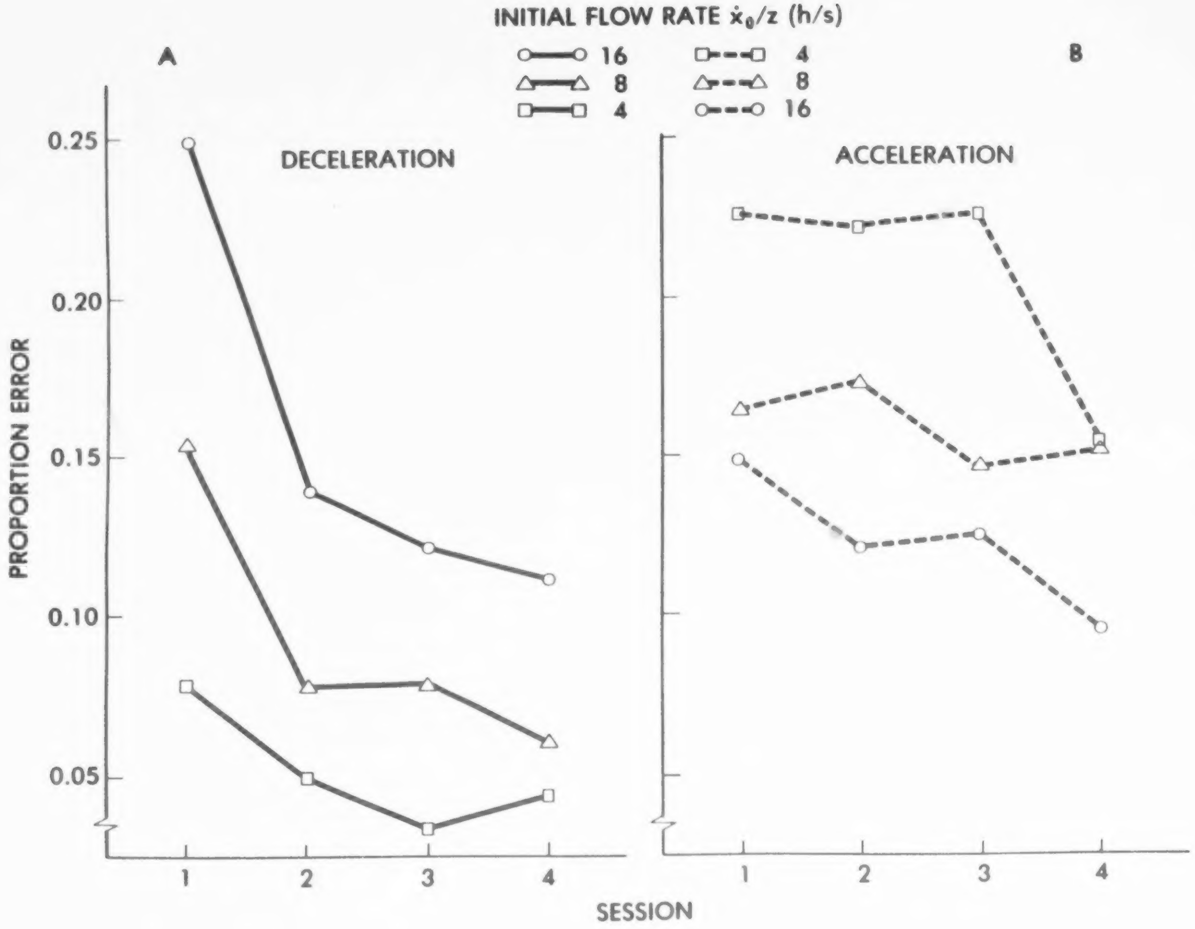

Figure III-7. Proportion error as a function of initial global optical flow rate and session for events representing decelerating (A) and accelerating (B) self motion.

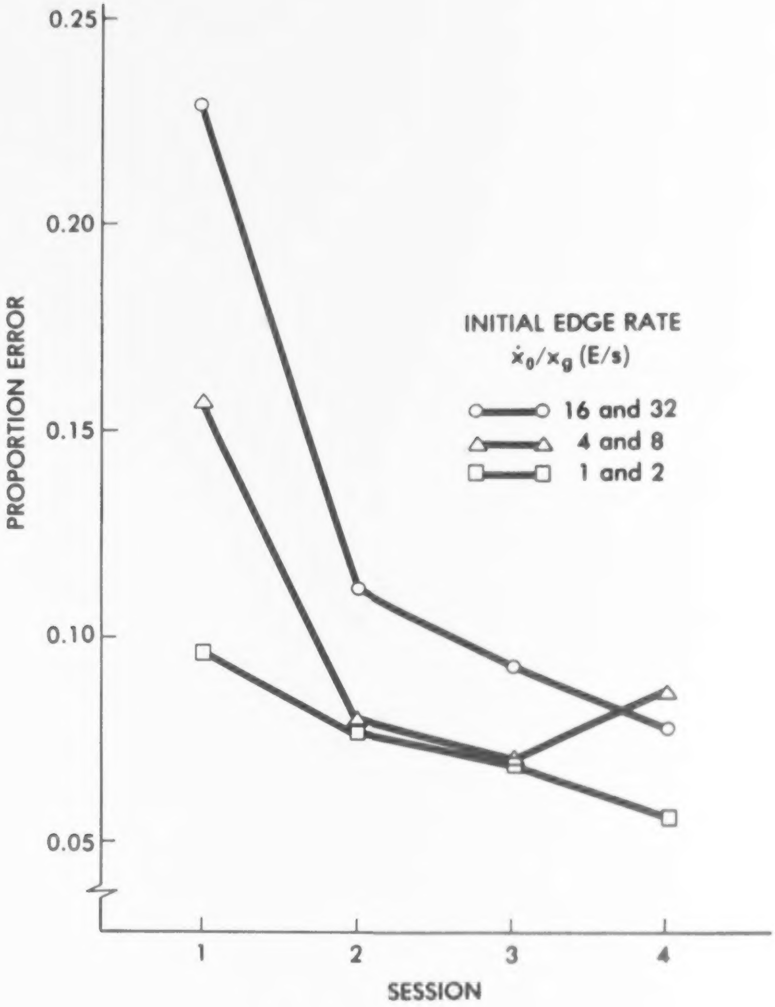

Figure III-8. Proportion error as a function of sessions and three pairs of initial edge rates for events representing decelerating rates of self motion.

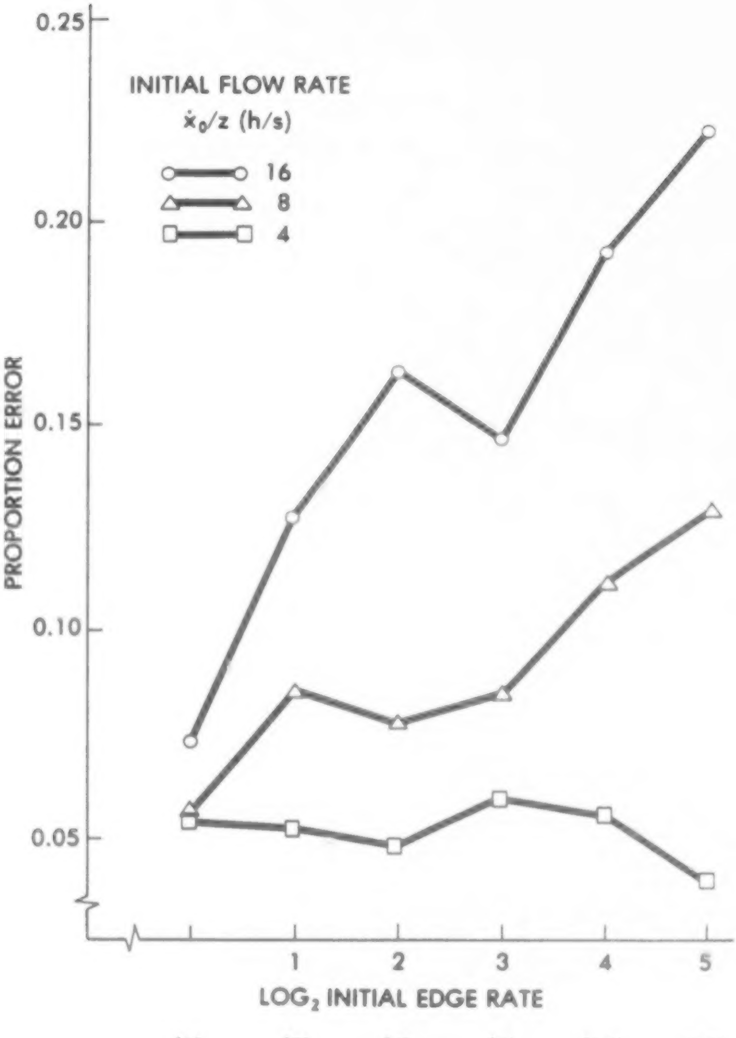

Figure III-9. Proportion error as a function of initial edge rate and initial flow rate for events representing decelerating self motion.

Corrective Response Variables

Slope of onset ramp. Two mixed-design analyses of variance were conducted on the slopes and revealed significant effects for session, initial flow rate, and initial fractional change. Figure III-10 shows that the slopes steepen with practice through the first three sessions. The slope for the fourth session is less steep than for the third, a pattern which is present for both accelerating and decelerating events. The effect of session on slope accounts for 2.55% for decelerating events and 0.68% for accelerating events. The effect of initial fractional change accounts for 0.80% and 0.76% of the variance in slope for the decelerating and accelerating events, respectively. The intercepts of the regression lines were not observed to be zero, as a result of the fact that the control actions did not instantaneously achieve the level of force at which they were maintained throughout the linear part of the corrective response phase. Figure III-11 shows that the slopes of the regression lines increase with higher fractional rates of change. Table III-2 shows that the opposite trend is present for error trials, and that the slopes are much less steep. The effect of initial flow rate shown in Figure III-12 reveals that higher flow rates result in steeper slopes. This pattern is present for both event types but is much more pronounced for acceleration events, accounting for 4.08% of the variance, as opposed to 0.32% of the variance for decelerating events.

Maintenance Variables

Following the initial response phase, the subjects attempted to maintain a constant velocity. The summary statistics calculated for the maintenance phase of active control include the means and standard deviations of velocity, acceleration, flow rate, flow acceleration, edge rate, edge acceleration and fractional change, computed from the point at which either the initial control action cancelled the forcing function or 300 ms had elapsed to the end of the trial. Separate analyses of variance were performed on each summary statistic for accelerating and decelerating events.

Velocity. The subjects were instructed to maintain a constant velocity throughout the duration of the event, by applying an

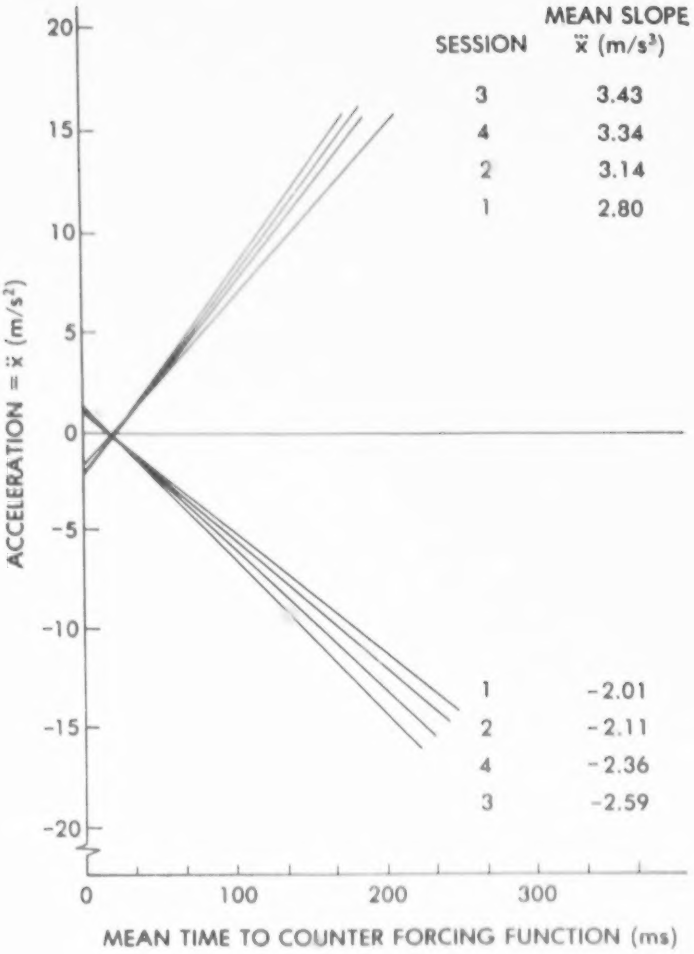

Figure III-10. Regression lines for controlled acceleration from reaction time until the mean time required to counter the forcing function for each session. The slope of each line is equal to the mean change in acceleration ($\dddot{x}$) during the initial corrective phase of performance.

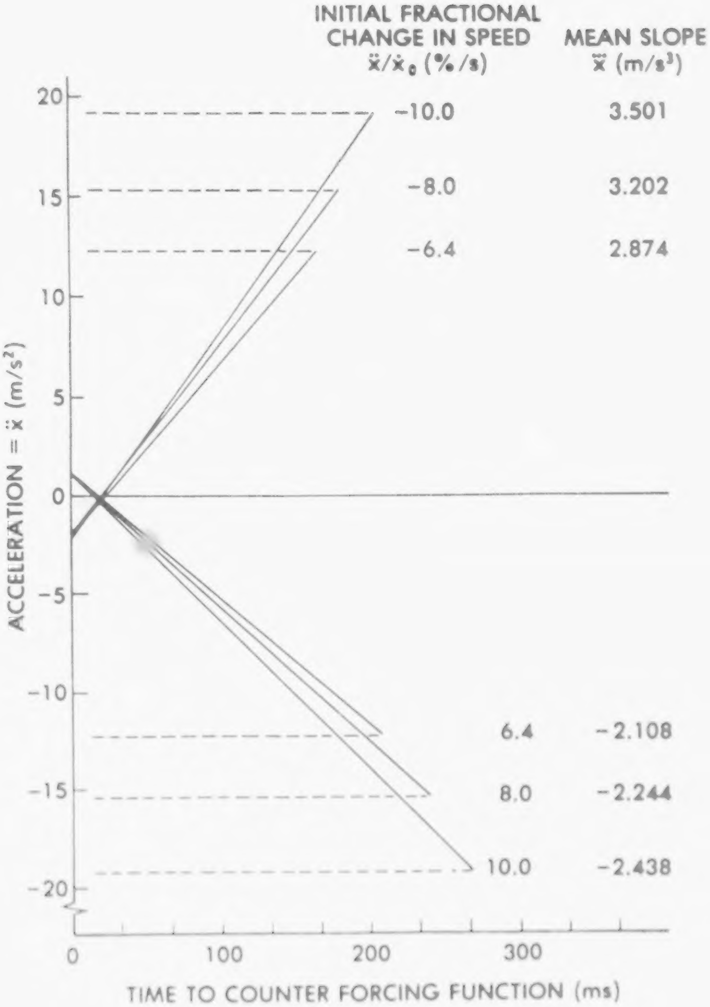

Figure III-11. Regression lines for controlled acceleration from reaction time until the forcing function had been countered (at the dashed line) for each level of initial fractional change in speed of self motion. The slope of each line is equal to the change in acceleration ($\dddot{x}$) during the initial correction phase of performance.

Table III-2

Slope of Initial Onset Ramp as a Function of Initial Fractional Change ($\ddot{x}/\dot{x}_0$)

	Correct Trials		Error Trials	
Initial fractional change ($\ddot{x}/\dot{x}_0$) (%/s)	Slope $\dddot{x}$ (m/s^3)	Number of trials	Slope $\dddot{x}$ (m/s^3)	Number of trials
	Deceleration			
-6.4	2.87	2263	-1.61	243
-8.0	3.20	2303	-1.53	211
-10.0	3.50	2277	-1.25	246
	Acceleration			
6.4	-2.11	1918	1.97	427
8.0	-2.24	1936	1.98	377
10.0	-2.44	2106	1.94	306

Note. A dot over a symbol indicates a derivative with respect to time. A subscript of zero indicates the value of a variable at the initiation of an event. The initial speed was 192 m/s for all events.

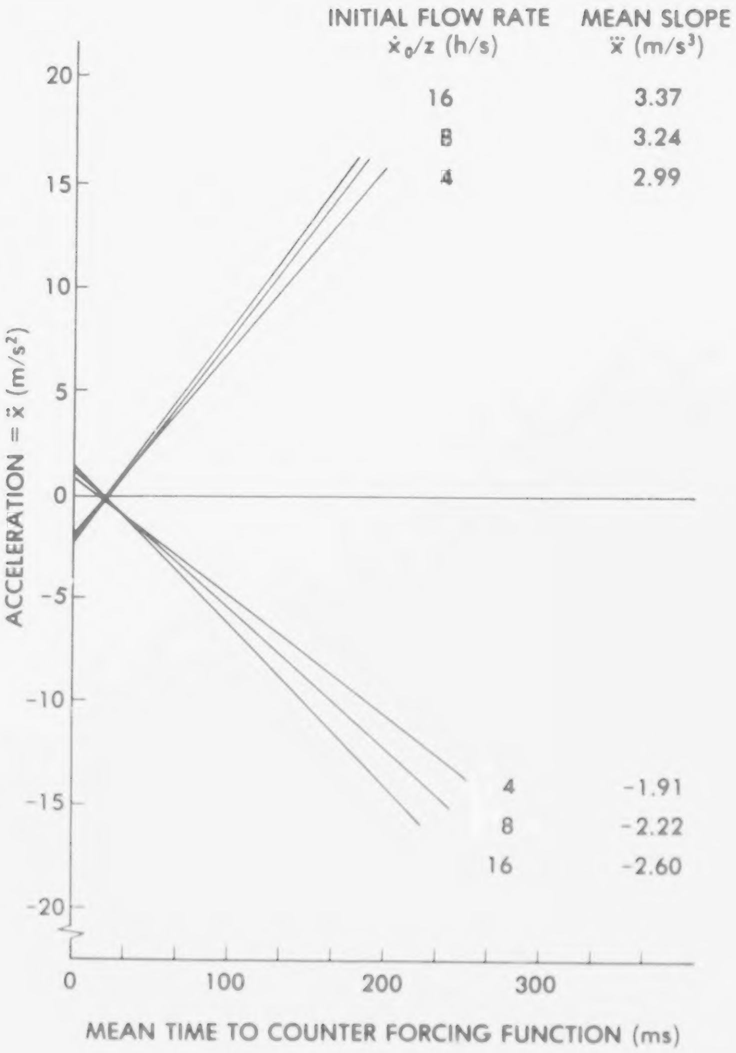

Figure III-12. Regression lines for controlled acceleration from reaction time until the mean time required to counter the forcing function for each level of initial flow rate. The slope of each line is equal to the mean change in acceleration ($\dddot{x}$) during the initial correction phase of performance.

appropriate force in the appropriate direction to cancel the computer-initiated change. For decelerating events, all main effects had a significant influence on mean velocity, and each accounted for at least 1.0% of the total variance. For accelerating events, the main effects of initial flow rate, initial edge rate, and initial fractional change were significant, but only initial flow rate and initial fractional change accounted for more than 1.0% of the variance in mean velocity. For decelerating events, mean velocity tended to increase across the first three sessions and then fall slightly on the fourth session.

The session main effects for decelerating and accelerating events accounted for 1.65% and 0.92% of the total variance in the standard deviation of velocity. For both event types, the standard deviation in velocity decreased with practice over the four sessions.

The effect of initial flow rate for decelerating events accounted for 1.44% of the variance, a rather modest effect when compared to the 19.83% of the total variance accounted for by initial flow rate during acceleration trials. This considerable difference notwithstanding, lower mean velocities were associated with higher initial flow rates for both event types, as shown in Figure III-13.

The interaction between initial flow rate and initial edge rate was also significant, accounting for 1.18% of the variance for accelerating events. The interaction reveals that higher initial edge rates resulted in lower mean velocities, but only under conditions of the highest initial flow rate. In general, there was no interpretable structure involving edge rate for decelerating events.

The effects for initial flow rate accounted for 1.13% and 3.75% of the variance in the standard deviations of velocity for decelerating and accelerating events, respectively. The effects for edge rate were also significant but accounted for a somewhat smaller percentage of the total variance in standard deviation of velocity; 0.81% and 0.55% for decelerating and accelerating events, respectively. The interactions between initial flow rate and initial edge rate were significant, accounting for 0.41% of the variance in standard deviation of velocity for decelerating events, and 0.69% of the variance for accelerating events. Figure III-14 shows a slight trend toward decreasing standard

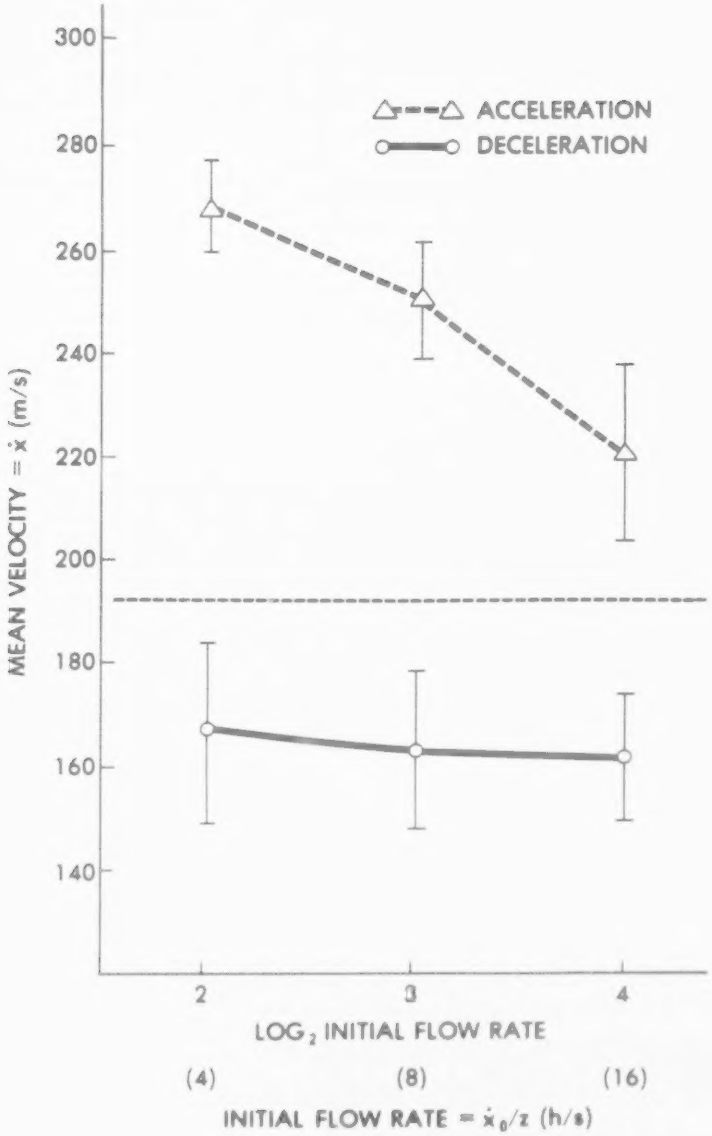

Figure III-13. Mean velocity produced during the maintenance phase of performance, as a function of initial flow rate for events representing accelerating and decelerating self motion. The vertical bars represent ±1 mean standard deviation in velocity. The dashed line at 192 m/s represents the initial velocity.

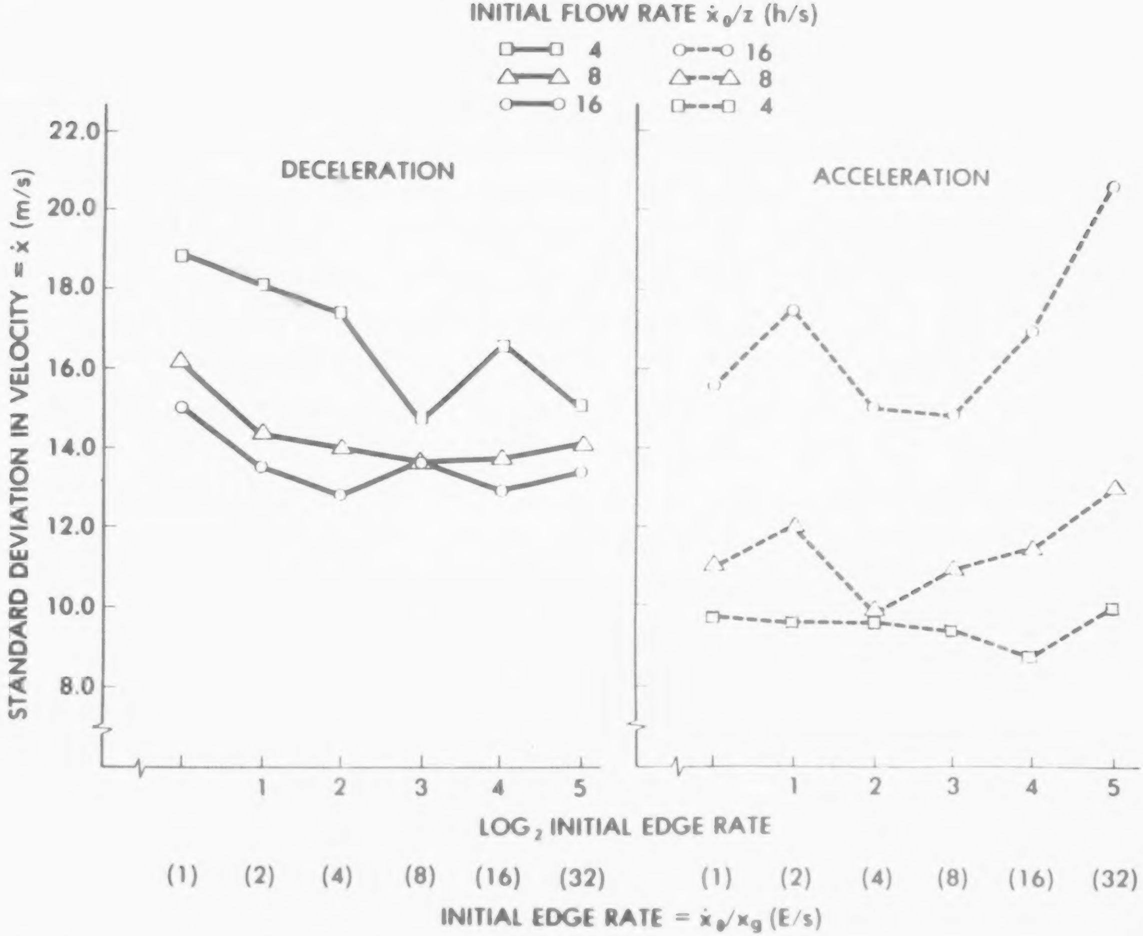

Figure III-14. Mean standard deviation in velocity produced during the maintenance phase of performance as a function of initial edge rate and initial flow rate for events representing decelerating and accelerating self motion.

deviations in velocity with higher initial edge rates and higher initial flow rates for accelerating events. On the other hand, for accelerating events, higher standard deviations were associated with higher initial flow rates. High initial edge rates also had the effect of producing higher standard deviations in velocity, but only when combined with high initial flow rates.

The effect of initial fractional change accounted for 6.24% and 5.75% of the variance in mean velocity for decelerating and accelerating events, respectively. Although the effect of initial fractional change might at first appear opposite for the two event types, Figure III-15 shows that the higher the initial fractional rate of change, the further the mean velocity is from the initial value of 192 m/s. Figure III-15 also shows the velocity at reaction time for each of the initial fractional changes, and the more pronounced tendency of velocity to drift back toward the initial starting velocity during decelerating events, although the drift was present with both event types.

Flow rate. The results of the flow-rate analysis were indistinguishable from the results of the velocity analysis, and the means differed only by the altitude scaler.

Edge rate. For decelerating trials, all main effects were significant, but only initial edge rate accounted for more than 1.0% of the variance in mean edge rate. The effect of initial edge rate, which accounted for 86.36% of the variance in mean edge rate, is due to the scale of ground texture employed and is thus largely an artifact.

Acceleration. The force stick used in this experiment was an acceleration controller, making the mean and standard deviation in acceleration particularly important dependent measures, because they directly assess the output of the participant's control actions. Perfect performance, in light of the task demand, involves achieving and holding a mean acceleration of 0.0 m/s. The main effects of initial flow rate, initial edge rate, and initial fractional change were significant and accounted for at least 1.0% of the variance in mean acceleration for decelerating events. For accelerating events, the main effects for initial flow rate and initial fractional change were significant, but only initial flow rate accounted for more than 1.0% of

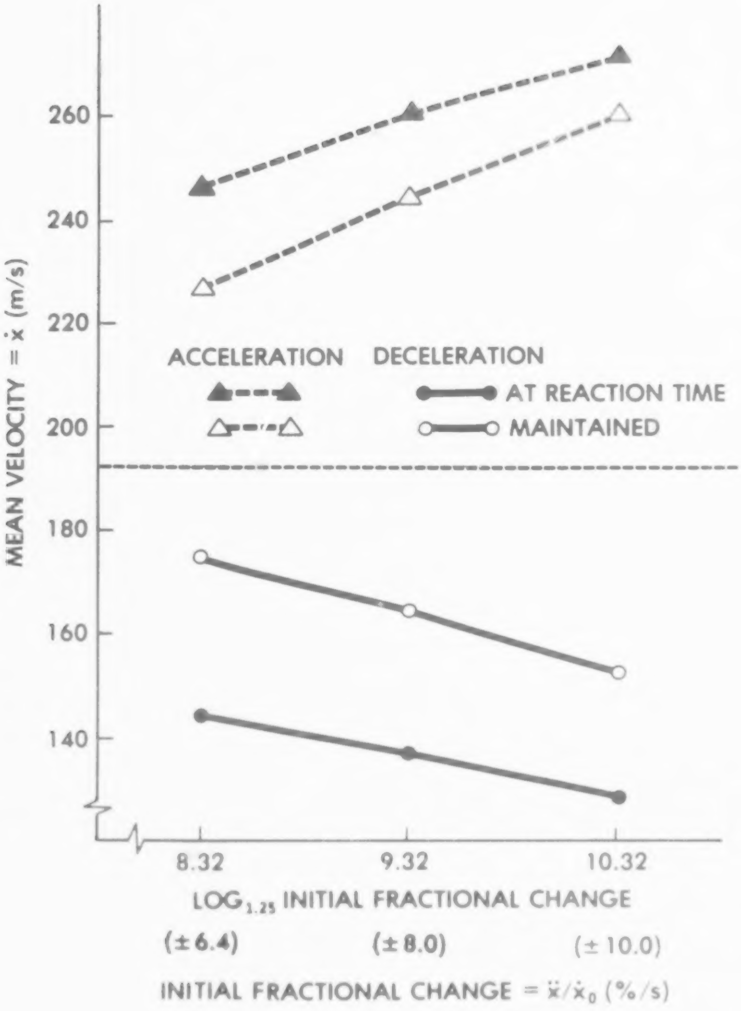

Figure III-15. Velocity at mean reaction time and mean velocity produced during the maintenance phase of performance as a function of initial fractional change in speed for events representing accelerating and decelerating self motion. Dashed line represents initial velocity.

the variance in mean acceleration. The overall tendency of the participants was to over-compensate for the detected changes in the rate of self motion, such that the mean acceleration rate was 6.97 m/s^2 during deceleration trials and -4.68 m/s^2 during acceleration trials.

Figure III-16 shows that performance improved with higher initial flow rates for decelerating events. However, initial flow rate had the opposite effect on accelerating events, as lower initial flow rates resulted in better performance. Initial flow rate accounted for 3.74% of the variance in mean acceleration for decelerating events and 8.51% of the variance for accelerating events. For decelerating events, initial flow rate accounted for 2.83% of the variance in the standard deviation of acceleration, and for decelerating events, 2.02% of the variance. Figure III-16B shows that higher standard deviations in acceleration are associated with higher initial flow rates for both decelerating and accelerating event types.

The effect of initial edge rate on acceleration for decelerating events (Figure III-17) illustrates that performance optimized at a midrange initial edge rate of 8.0 edges/s. The main effect accounted for 1.0% of the variance in mean acceleration. The effect of initial edge rate for accelerating events failed to reach significance; but the overall trend of the function was similar to results obtained for decelerating events, with performance optimizing at a midrange value of 4.0 edges/s.

The effects of initial fractional change for decelerating and accelerating events accounted for 1.17% and 0.41% of the variance in maintained acceleration, respectively. Figure III-18 shows that performance improved with higher fractional rates of change for both event types.

For standard deviation in acceleration, the effects of session and initial flow rate were significant and accounted for more than 1.0% of the variance for both event types. The session effect accounted for 1.94% and 1.37% of the variance in the standard deviations in acceleration for decelerating and accelerating events, respectively. It is evident in Figure III-19 that the standard deviation in acceleration decreased with practice for both event types.

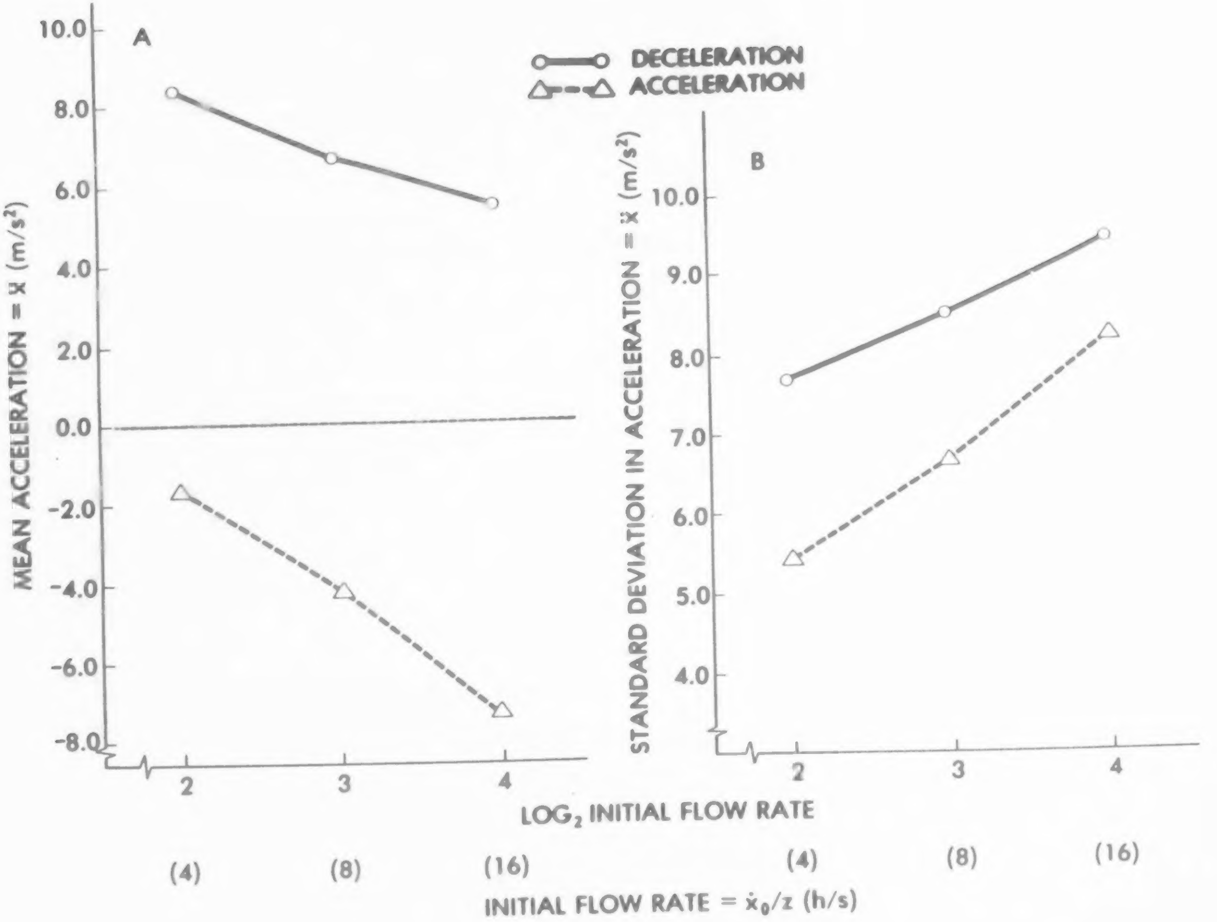

Figure III-16. Mean acceleration (A) and mean standard deviation in acceleration (B) produced during the maintenance phase of performance as a function of initial flow rate for events representing accelerating and decelerating self motion. Dashed line in panel A represents perfect performance.

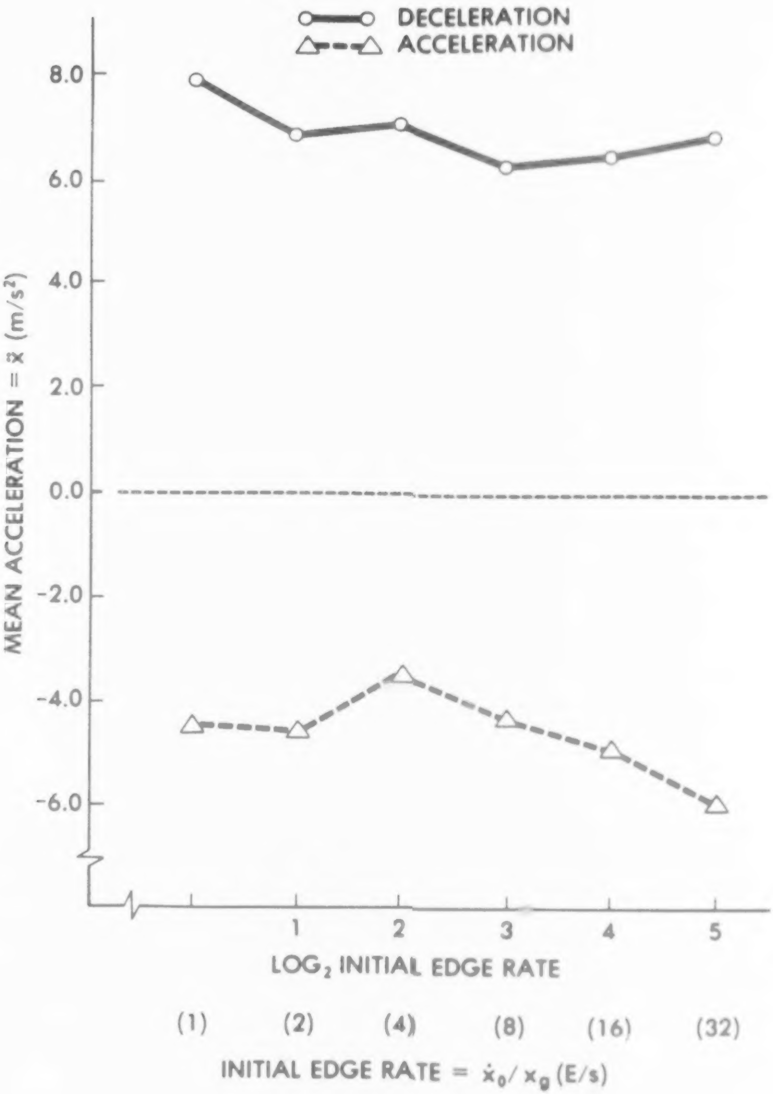

Figure III-17. Mean acceleration produced during the maintenance phase of performance as a function of initial edge rate for events representing accelerating and decelerating self motion. Dashed line at 0 m/s^2 represents perfect performance.

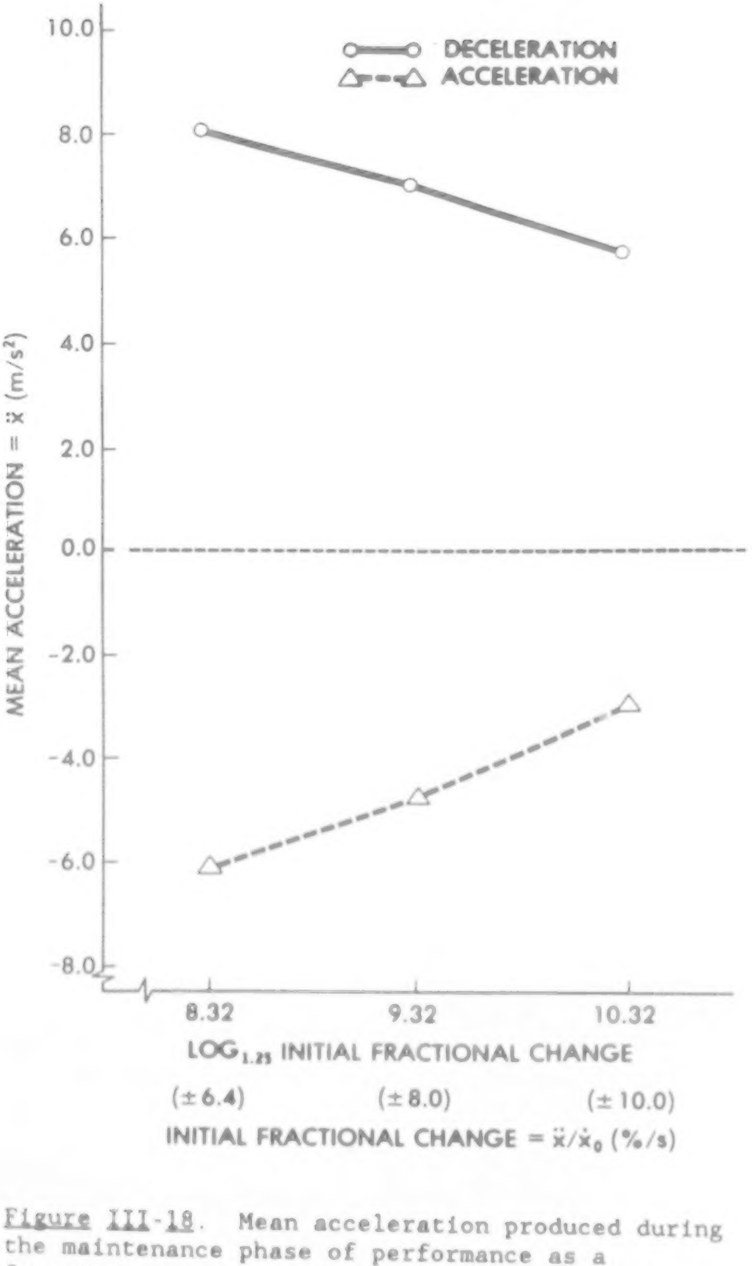

Figure III-18. Mean acceleration produced during the maintenance phase of performance as a function of initial fractional change in speed for events representing accelerating and decelerating self motion. Dashed line at 0 m/s^2 represents perfect performance.

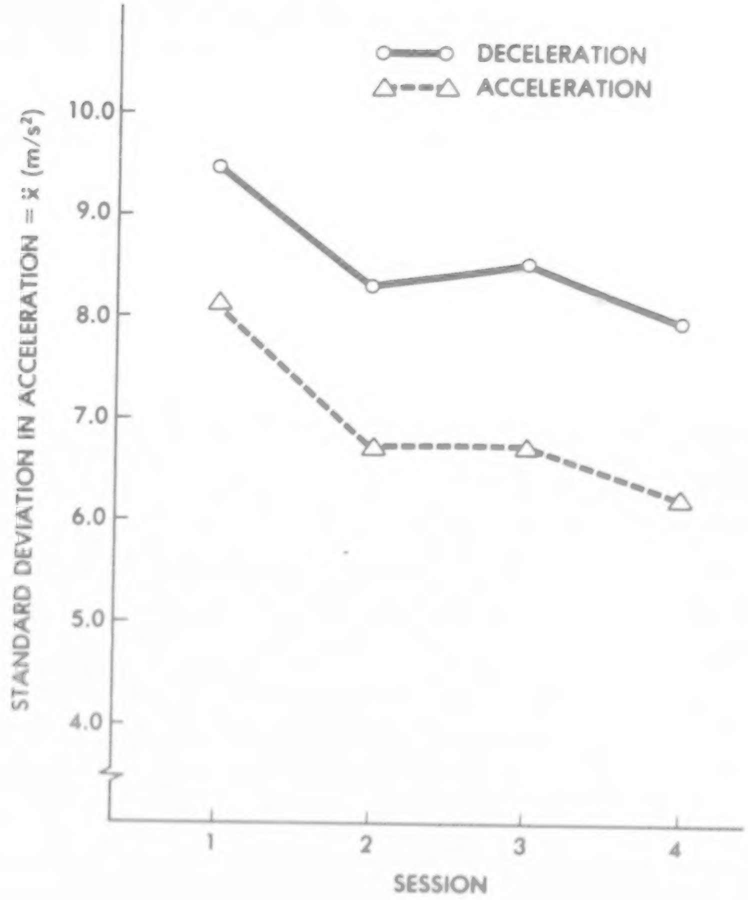

Figure III-19. Mean standard deviation in acceleration produced during the maintenance phase of performance as a function of session for events representing accelerating and decelerating self motion. Dashed line at 0 m/s^2 represents perfect performance.

Flow acceleration. Maintained flow acceleration differs from acceleration by only the altitude scaling factor. Results for mean and standard deviations of flow acceleration were similar to those for mean and standard deviation in acceleration.

Edge acceleration. Since maintained edge acceleration, when used as a dependent measure, differs from acceleration by merely a scaling factor, results of the analyses of the mean and standard deviation of edge acceleration were similar to those of the mean and standard deviation in acceleration, with the exception of the main effect of initial edge rate which resulted as an artifact of difference in ground-texture scaling of acceleration.

Fractional change. The main effects of initial flow rate, initial edge rate, and initial fractional change were significant for both event types. For decelerating events, higher flow rates resulted in better performance; whereas for accelerating events, higher flow rate resulted in worse performance. The effects of initial flow rate on mean fractional change were similar to the effects that initial flow rate had on mean acceleration, differing only by a speed scaling factor (see Figure III-16). For both accelerating and decelerating events, performance was better with higher initial fractional rates of change. The effect that initial fractional change has on the mean maintained fractional change is similar to the effect that initial fractional rate of change has on mean acceleration, as shown in Figure III-17. No interpretable structure could be found in the effect of initial edge rate on mean fractional rate of change. No significant results were obtained in the analysis of the standard deviation in fractional rate of change.

Summary

In general, all three optical independent variables of interest (initial flow rate, initial edge rate, and initial fractional change in both) had appreciable effects on performance. The grain of analysis becomes finer as the participants' performance is examined in the various phases in the response sequence, and it becomes apparent that different optical variables exert their influence at different stages. The influence of initial fractional rate of change on the accuracy of the initial direction of response was quite modest compared to the large additive effects that both initial flow rate and initial edge rate had during the initial stage of performance. The effects of initial flow rate on initial edge rate, while larger, are, however, greatly reduced with practice.

During the corrective response phase, the influence of initial fractional rate was greatly increased whereas the effects due to initial edge rate became negligible. Initial flow rate continued to exert an appreciable influence on performance during the corrective response phase.

Finally, during the maintenance phase of performance, the three optical variables could be seen to influence different aspects of control behavior. Both initial flow rate and initial fractional rate of change had a pronounced effect on the velocity being maintained throughout the remainder of the event, whereas initial flow rate and initial edge rate had an effect on the standard deviation variation in velocity. With respect to the overall accuracy of performance during the maintenance task, however, it can be seen that all three optical variables had a substantial influence on acceleration control.

Table III-3 summarizes the results of mean velocity ($\dot{x}_s$), mean acceleration ($\ddot{x}_s$), and mean fractional rate of change ($((\ddot{x}/\dot{x})s)$). The control task required the subject to counter the forcing function ($\ddot{x}_t$) with enough force to keep the fractional rate of change equal to zero. In other words, the closer the fractional change is to zero the better the performance. Table III-3 illustrates that the higher the initial fractional rate of change, the better the performance, regardless of the mean velocity; for the best performance was associated with the highest velocity on accelerating events and with the lowest velocity on decelerating events. Performance varied with the level of acceleration and initial fractional change.

Discussion

A number of major points can be made concerning the significance of the results, and they will be organized according to the sequential stages of the control performance. The effects of initial flow rate,

Table III-3. Summary of Maintenance Variables[a]

$\ddot{x}_t$	$\ddot{x}_t/\dot{x}_o$	$(\dot{x}/\dot{x})_{RT}$	$\ddot{x}_{cntl}$	$\ddot{x}_s$	/	$\dot{x}_s$	=	$\ddot{x}/\dot{x}_s$
				Deceleration				
-12.288	-.64	- 8.5	20.4	8.11	/	174.7	=	4.6
-15.360	-8.0	-11.2	22.4	7.04	/	165.8	=	4.2
-19.200	-10.0	-14.9	25.0	5.78	/	153.2	=	3.8
				Acceleration				
12.288	6.4	5.0	-18.4	-6.16	/	226.8	=	-2.7
15.360	8.0	5.8	-20.2	-4.38	/	244.6	=	-2.0
19.200	10.0	7.0	-22.2	-3.05	/	261.9	=	-1.1

Note. A dot over a symbol indicates a derivative with respect to time. A subscript of zero indicates the value of a variable at the initiation of an event. The subscript *t* indicates the value of a variable at any time during the event, and the subscript *s* (for state of the system) indicates the value of the sum of forcing function plus control output. The initial velocity was 192.0 m/s for all events.

[a] Variables

1. $\ddot{x}_t$ = forcing function (m/s^2).
2. $\ddot{x}_t/\dot{x}_o$ = initial fractional change in speed (%/s).
3. $(\ddot{x}/\dot{x})_{RT}$ = fractional change in speed at reaction time (%/s).
4. $\ddot{x}_{cntl}$ = total control output (m/s^2).
5. $\ddot{x}_s$ = mean acceleration during the maintenance phase of performance (m/s^2).
6. $\dot{x}_s$ = mean velocity during the maintenance phase of performance (m/s).
7. $(\ddot{x}/\dot{x})_s$ = mean fractional change in speed during the maintenance phase of performance (%/s).

initial edge rate, and initial fractional change on performance during the initial response phase are considered first, along with a discussion of the practice effect that influences the subject's control behavior during that phase. Next, the influence of initial flow rate and initial fractional change on performance during the corrective response phase is discussed, followed by an assessment of the influence of optical variables on the maintenance phase of performance in which the implications of the results for the ecological approach to perceiving and acting are examined.

Response Initiation Phase

The results of performance during the response initiation phase clearly point to the difference between functional and contextual variables, as well as the consequences of treating what should be contextual variables as though they were functional variables. A functional variable has been defined as any variable that both provides information relevant to the performance of the task at hand (Owen, 1985), and is a parameter of stimulation to which the individual is attuned. The functional variable for a particular task is specific to an event parameter, such that the detection and control of the variable will lead to performance that is considered correct or effective under the conditions of the particular task. The results of judgment studies designed to assess sensitivity to optical variables have shown thus far that functional variables are without exception both relational, in the sense that non-arbitrary relationships between the individual and the environment are preserved, and relative, in the sense that they are not specific to either absolute optical or event variables. The functional variables identified from prior studies have all been fractional rates of change.

Functional variable. Although the task employed in the present effort differs in several respects from the tasks employed in previous studies by virtue of the fact that the participants were required to distinguish a positive rate of change from a negative one rather than simply distinguishing a change in speed from an event depicting constant speed, the results are largely in accordance with previous findings. By definition, an increase in the magnitude of a functional variable results in increasingly better performance, and a decrease in magnitude leads to increasingly poorer performance. Examination of both panels in Figure III-5 indicates that initial fractional change in speed has this characteristic of a functional variable. It is evident that performance during the initial response phase improves by getting either faster or more accurate with higher levels of initial fractional rates of change.

Although our results are in general agreement with those from earlier judgment studies (Owen et al., 1984; Tobias & Owen, 1984), two major differences stand out. The first difference involves the existence of shorter reaction times and better accuracy for the interactive study when compared to results of earlier judgment studies. Reaction times were nearly a full second shorter, and errors in the direction of response were approximately 25% less than observed by either Tobias and Owen (1984) for the same fractional losses, or Owen et al. (1984) for similar fractional gains. These findings may have been the result of differences in the task demands, and the fact that it may have been easier to distinguish instances of accelerating and decelerating self motion than it was to distinguish a change in speed of self motion from an event representing constant speed. The second major difference involves that fact that in the present experiment, the magnitude of the effect related to the functional variable was greatly diminished. For deceleration events, the improvement in performance that resulted from an increase in the level of initial fractional change occurred only in the speed of the response. Acceleration events showed the opposite trend; i.e., substantial improvements in accuracy occurred with increases in the level of fractional change, with only minimal improvement in the speed of the response.

A possible explanation for the lack of improvement in accuracy for decelerating events involves the existence of a floor effect bending a function which might otherwise display the characteristic equal-interval improvement in performance that accompanies equal-ratio increments in the level of a functional variable. Although Tobias and Owen (1984) reported substantial improvements in both the accuracy and the speed of response for the detection of deceleration in self motion over identical initial fractional rates of change, the somewhat more restricted range of values of initial global optical flow rate employed in their study is likely to account for the discrepancy in results. High values of initial flow rate are known to have a deleterious effect on sensitivity to information specifying a loss in speed of self motion (see Figure III-4), and the present investigation employed a value of initial flow rate nearly twice the highest value used by Tobias and Owen. Thus, the high flow rates may have overshadowed the effects of varying magnitudes of initial fractional changes so that performance reached a baseline error rate of approximately 10%.

The lack of difference in reaction times for the acceleration events is likely to be due to the fact that with constant acceleration, fractional change decreases exponentially over time; i.e., the faster the acceleration rate, the faster the exponential decrease in fractional change such that, by reaction times, initial fractional changes equal to 6.4%, 8.0%, and 10 %/s have been reduced to 5.0%, 5.8%, and 7.0 %/s, respectively. Thus, the magnitude of the effect is understandably reduced.

Dysfunctional variables. In addition to relevant functional variables which provide salient information for distinguishing and controlling actions, there is a second class of event variables that have also been shown to influence sensitivity during performance of perceptual and motor tasks. Optical variables that are irrelevant for the performance of a particular task have been shown, in certain instances, and at certain levels, to interfere with the performance of that task (Hettinger et al., 1985; Owen et al., 1984). There must, for example, be an optical flow rate available as background information in order to detect a change in rate of self motion. However, the global optical flow rate is altitude-scaled information about self motion, which, although optically available, does not itself specify the change in the speed of self motion. Global optical flow rate is thus merely an irrelevant optical variable which has been shown to interfere with the individual's ability to detect changes in the rate of self motion (Tobias, 1983; Tobias & Owen, 1984). Under the task requirements employed in the present experiment, both flow rate and edge rate information are irrelevant sources of information for the detection and control of changes in speed of self motion.

Examination of the results of performance during the initial response phase indicates that, in some cases, the participants were treating irrelevant sources of information as though they were relevant for the performance of the intended task. This relationship constitutes the specification of a dysfunctional variable. High values of initial optical flow rate apparently look like acceleration, and the participants are evidently distracted by these high values to the point that sensitivity to information specifying loss in speed is adversely affected (see Figure III-4A). Under conditions of accelerating speed, high values of initial flow rate benefit the detection of a gain in speed, and high flow rate is, once again, incorrectly perceived as acceleration. Figure III-4B is important for illustrating the fact that the difference in accuracy for accelerating and decelerating events is due to the influence of the contextual variable global optical flow rate, and not merely a speed-accuracy trade-off.

An examination of Figure III-9 reveals the deleterious effects of extreme values of two different contextual variables, initial flow rate and initial edge rate. At a low flow rate, edge rate had essentially no influence on sensitivity to information specifying loss in speed, but at higher flow rates the effects of high edge rate were substantial. The participants' sensitivity to the functional variable was markedly reduced by their attunement to sources of information which were irrelevant to the performance of the intended task.

Improvement. Accuracy of the initial response improved substantially with practice as shown in Figure III-6. It is also important to note that reaction times did not vary significantly across sessions, thus ruling out the possibility of a speed-accuracy trade-off that would accompany a shift in response criterion. The participants were simply learning to distinguish deceleration from acceleration with greater accuracy, without requiring longer amounts of time to make the distinction. Since reaction times typically become shorter with practice, the participants must have learned to let the events unfold sufficiently to ensure accuracy. Figures III-7 and III-8 indicate that the noted improvement resulted from the participants' apparently learning what optical information was relevant and what optical information was irrelevant for accurately detecting changes in the rate of self motion. This observation is important within the theoretical framework of the ecological approach to learning, for it illustrates an ability on the part of the participants to learn directly from observing the consequence of their actions. According to the ecological approach to learning, improvement in performance that results from an ability to distinguish relevant from irrelevant information is acquired through an interaction with environment (Gibson, 1969). As emphasized by Owen (1987a), when an individual controls optical stimulation in an attempt to achieve a specific perceptual outcome, direct feedback will be obtained by simply seeing the consequence of the actions used to control stimulation. Detection of a discrepancy between the intended outcome and what is subsequently perceived should be sufficient to enable the individual to improve performance, if the individual is able to adjust control behavior during ensuing perception-action cycles in ways that reduce the discrepancy. Learning consists of improvements both in sensitivity to variables of stimulation and in the skills needed to control stimulation, and as such, is indexed by improvements in the ability to detect and control the information in stimulation. These findings demonstrate the fact that the participants were learning to differentiate between relevant and irrelevant optical variables that had initially been treated as equivalent or equally relevant sources of information specifying a change in the rate of self motion.

Corrective Response Phase

The results from judgment studies involving the detection of either acceleration or deceleration in speed (Owen et al., 1984; Tobias & Owen, 1984; Warren et al., 1982) have shown that as error rates and reaction time decrease with higher levels of the functional variable, confidence ratings increase linearly. Under the present conditions, performance was also shown to improve with higher levels of fractional change and, as Figure III-11 reveals, the steepness of the slope of the onset ramp increased with higher levels of the functional variable. The results shown in Table III-2 also illustrate the relationship between the steepness of the onset ramp and accuracy of the control action. On error trials, the slopes of the onset ramps were substantially shallower than they were during correct response trials. The results of performance during the corrective response phase suggest that the slope of the onset ramp is a behavioral index of the participants' confidence. It is reasonable to assume that the more confident the participants were about the characteristics of the rate change in self motion that they were experiencing, the more force they imparted to the control stick in order to achieve the desired correction. The greater the force being applied to the control stick, the output of which is expressed in meters per second squared, the steeper the slope of the onset ramp in meters per second cubed.

In addition to differences in the amount of force being applied to the control stick that vary as a function of the fractional change, it is also apparent that the amount of force used during the corrective phase of performance increases with practice. Increase in the amount of force applied produces an increase in the steepness of the slopes that parallels a decline in error rates across session. Although no direct comparison between confidence ratings and error rates across session can be made in this experiment, the existence of a linear relationship between error rates and confidence ratings in prior judgment studies lends additional support to the belief that the steepness of the slope is a behavioral index of confidence. With repeated exposure, this increased confidence is likely to be expressed behaviorally in terms of the participants' learning of (a) the amount of control needed to counter the forcing function, and (b) the quickest way to achieve the desired results. Thus, with practice, the error rates drop and the slopes become steeper as the participants become more confident.

The reciprocal relationship between steepness of the slope of the onset ramp and confidence does not, however, appear to be the only explanation, as several additional factors seem to influence the amount of force being applied to the control stick. For example, the decline in steepness of the slope between the third and fourth session may be a result of an effort on the part of the participants to optimize their performance during the maintenance phase by reducing the magnitude of the control overshoot (Clark & Stark, 1975) (see Figure III-1).

The influence of initial global optical flow rate on the slope of the onset ramp is more difficult to interpret. Figure III-11 reveals effects of initial flow rate on the steepness of the ramp during acceleration events that are consistent with the belief that ramp slope is a behavioral index of confidence. An examination of the results from judgment studies involving the detection of gain in the rate of self motion (Owen et al., 1984) indicates that both confidence ratings and accuracy increase with higher levels of initial flow rate, exhibiting a linear relationship between accuracy and confidence ratings. In the present investigation, both the accuracy and the amount of force used to counter the forcing function increased with higher levels of initial flow rate, again suggesting that the amount of force that the participants imparted to the control stick increased with an increase in their confidence.

The influence of initial global optical flow rate on the steepness of the ramp slope during deceleration events does not, however, appear to follow the same trend. Performance during the initial response phase was adversely affected by higher levels of initial flow rate, while the results indicate that the steepness of the slope increased with higher levels of initial flow rate. To be consistent with the preceding argument concerning the relationship between the steepness of the onset ramp and the participants' confidence, higher initial flow rates would be expected to result in shallower slopes, rather than the steeper slopes observed. Results of the Tobias and Owen (1984) judgment study also failed to show any consistent relationship between confidence ratings and initial flow rate for deceleration events.

Maintenance Phase

According to the ecological approach to perception, perceiving is defined in terms of a reciprocal relationship between the perceiver and the environment to be perceived. Visual perception is considered to be anchored to the optic array and to involve the entire individual in the acquisition of information. Rather than being narrowly construed as an activity occurring solely within the nervous system, perception is conceived to be an integral part of the perception-action cycle. From the perspective of the perceptual side of the perception-action cycle, the purpose of an action is to control stimulation until an intended perceptual outcome is achieved (Gibson, 1958). Since the structure of stimulation is considered to be specific to the structure of the environment and the individual's relationship to it (Gibson, 1966), controlling stimulation effectively will result in intended relationships between the individual and the environment (Owen, 1985). The control of stimulation might, for example, involve performance of actions necessary for the perception of a zero fractional rate of change in self motion if the desire is to maintain a constant speed.

Functional variable. Because of the nature of the reciprocal relationship between perception and action, the ability of an individual to control the rate of self motion will at least in part be linked to his or her sensitivity to the available optical information specifying the rate of self motion. Optimum performance for the task of maintaining constant velocity involves achieving a mean acceleration rate of 0.0 m/s^2, and Figure III-18 reveals that performance improved with higher initial fractional rates of change for both event types. Thus, as the participants' ability to detect changes in speed of self motion improved with higher levels of the functional variable, their ability to control the change also improved, suggesting that the easier the parameters of an event are to detect, the easier they will be to control.

Although the task in this experiment required the participants to maintain a constant velocity, Figure III-15 illustrates a general tendency on the part of the participants to overcompensate for detected changes in the speed of self motion. This tendency to overcompensate causes the velocity being maintained to drift toward the initial velocity during the course of the event. In addition to showing the existence of a drift in velocity during the course of the event, Figure III-15 also illustrates the fact that the magnitude of the drift varied across levels of the functional variable. While the velocities at reaction time were further from the initial velocity of 192 m/s for higher initial fractional rates of change, slightly smaller amounts of drift were associated with higher levels of the functional variable. Since optimum performance is characterized by the ability to maintain a constant velocity, and since smaller amounts of drift in velocity during the maintenance phase of performance indicates a closer approximation to this ideal, it is thus apparent that higher levels of the functional variable result in better performance. This observation, taken in conjunction with the results showing improvements in sensitivity to changes in speed with higher levels of the functional variable, again indicates that the easier the change in the speed is to detect, the easier it is to control.

In addition to the influence of initial fractional change on performance, it is also apparent that performance during the maintenance phase of acceleration events was consistently superior to performance during the maintenance phase of deceleration events. This finding appears to be contrary to the argument that the easier a change is to detect, the easier it is to control. As expected, performance in terms of both the accuracy and speed of the initial response was better during deceleration events. This observation can be explained by the fact that the magnitude of the functional variable was increasing exponentially prior to participants' responses during deceleration, but decreasing exponentially during acceleration events. However, once the participants had corrected for the change in their rate of self motion, they seemed better able to maintain a constant velocity under conditions of a constant positive forcing function than they were when confronted with a constant negative forcing function.

Although this observation does appear to be contrary to the argument that the easier the change is to detect, the easier it is to control, there is at least one possible explanation that would account for the present findings: the prevailing tendency on the part of participants to overcompensate for detected changes in the rate of self motion. Because of this tendency to overcompensate, events initially having characteristics that optically specified a loss in the rate of self motion (i.e., a negative fractional rate of change that was exponentially increasing in magnitude) eventually acquired the optical characteristic of an event with a gain in speed (see Figures III-1 and III-2). Conversely, events initially having characteristics that optically specified a gain in the rate of self motion (i.e., a positive fractional rate of change that was exponentially decreasing in magnitude) eventually acquired, as a result of the participants' overcompensation, the characteristics of an event with a loss in speed. This reversal in event characteristics would presumably make a change in speed, during what had originally been defined as an acceleration event on the basis of the forcing function, easier to detect because of the presence of a participant-induced exponential increase in magnitude of the functional variable. Thus, in accordance with the hypothesis that the easier the kinematics of an event are to detect, the easier they are to control, what had been originally defined as an acceleration event on the basis of the forcing function, would often become easier to control than deceleration events during the maintenance phase of performance because of the tendency of the participants to reverse the event characteristics by overcompensating for the detected change.

Dysfunctional variables. The optical variables that influenced the participants' sensitivity to changes in the rate of self motion during the initial response phase were also seen to influence performance during the maintenance phase of the control action. Although an irrelevant source of information, high initial flow rates and edge rates were often treated as though they were functional variables for the task of detecting and controlling changes in the rate of self motion. High flow rates and edge rates were perceived as instances of acceleration, leading the participant to respond to positive fractional rates of change with an increased amount of force. Thus, the tendency on the part of participants to overcompensate for detected changes in the rate of self motion is magnified by high values of initial flow rate. The net result is a substantially higher, but negative, mean acceleration and a lower mean velocity for acceleration events.

For decelerating events, the ability of the participant to detect a loss in speed was adversely affected by the irrelevant altitude-scaled information. As a result of attending to the irrelevant flow-rate information, the participants respond to negative fractional rates of change with smaller amounts of force. This has the effect of reducing the characteristic tendency of the participants to overcompensate for changes in the rate of self motion. While the irrelevant flow rate information had the effect of producing higher error rates in the initial direction of response and thus poorer performance during the initial response phase of the task, the effect of flow rate, when combined with the tendency of the participants to overcompensate for detected changes in the rate of self motion, resulted in a mean acceleration rate which was closer to zero. Thus, better average performance was achieved during the maintenance phase of the control task as a result of higher levels of initial flow rate. However, while higher values of initial flow rate had the effect of improving performance for deceleration events and worsening performance for acceleration events, overall performance during the maintenance phase (in terms of both mean acceleration and variation in acceleration) was better for acceleration events, irrespective of the influence of flow rate.

Contextual variables have in the past been operationally distinguished from functional variables on the basis of the structure of the psychophysical functions that were produced (Hettinger et al., 1985; Tobias, 1983; Tobias & Owen, 1984). As previously mentioned, increasing the magnitude of a functional variable results in increasingly better performance. In contrast, contextual variables typically produce either flat functions, when they do not influence sensitivity, or optimizing functions (in which very low or very high values result in poorer performance than do the midrange values), when they do influence sensitivity (Owen, 1985). Figure III-17 reveals the only instance in this study in which an irrelevant contextual variable produced an optimizing function (and did not amount to much). The predominant result is, however, one which indicates that both initial flow rate and initial edge rate produce functions more characteristic of what has been defined as a dysfunctional variable, as shown in Figures III-9 and III-16. Increasing the magnitude of a dysfunctional variable results in increasingly poorer performance. While both initial flow rate and initial edge rate should be contextual variables for the particular task of detecting and controlling changes in the speed of self motion (in that both provide irrelevant information), it is apparent that they are more often incorrectly used, as though they were functional information specifying a change in the rate of self motion. The participants frequently failed to differentiate between both the altitude-scaled and ground-texture-scaled information (neither of which specifies a change in the speed of self motion) and the fractional rate of change in speed (which does optically specify a change in the rate of self motion). When irrelevant information is treated as a contextual variable, it has a tendency to influence sensitivity, making it slightly poorer if the level is extreme. However, when irrelevant information is treated as functional information, the result is misinformation and ineffective performance of the intended task.

Control variability. In addition to the influences that initial flow rate and initial edge rate had on mean velocity and acceleration during the maintenance phase of performance, it was also apparent that they had an effect on the variability of control performance. In general, the standard deviation in the acceleration rate declined across sessions, as shown in Figure III-19, indicating that with practice the participants learned to achieve the same levels of accuracy while producing fewer control adjustments, control adjustments of a lower magnitude, or both. However, in spite of this general improvement, initial flow rate had the effect of producing greater variability in acceleration with higher initial values. This result again suggests that irrelevant altitude-scaled information has a deleterious influence on the ability to maintain a constant speed of self motion.

The influence of initial flow rate and initial edge rate on produced variability in velocity for accelerating events appears to be consistent with the results of the influence of flow rate on the standard deviation in acceleration. In both instances, variability in maintenance performance increased with increasing levels of initial flow rate. These findings are consistent with the idea that irrelevant altitude-scaled information adversely affected both the participants' sensitivity to changes in the rate of self motion and the ability of the

110

participants to maintain a constant speed under conditions of a constant positive forcing function.

The interaction between initial flow rate and initial edge rate suggests that irrelevant edge rate also had a deleterious effect on performance during the participants' attempts to maintain a constant velocity under conditions of a constant positive forcing function. Following the pattern of errors in Figure III-9, it is apparent that variability in velocity increased with both higher initial flow rates and higher initial edge rates.

Variability in velocity during deceleration events resulting from the influence of initial flow rate and initial edge rate is, however, a bit more difficult to explain. The influence that initial flow rate has on variability in velocity appears to be inconsistent with the influence that it has on variability in acceleration. Rather than producing greater variability, high values of initial flow rate result in lower variability in velocity. In light of the fact that ground-texture-scaled information failed to have a substantial effect on constant error during the maintenance phase of performance and had only a limited influence on variable error, it seems reasonable to conclude that the participants were more sensitive to altitude-scaled information than they were to ground-texture-scaled information, although both, as previously mentioned, were irrelevant sources of information. This difference in sensitivity is indexed by differences in performance, for irrelevant flow-rate information had a much larger deleterious influence than did irrelevant edge-rate information on the participants' overall ability to maintain a constant rate of self motion.

Summary and Conclusions

This experiment illustrates the usefulness of the interactive paradigm as a technique for investigating the perception-action cycle. From the perspective of the perception-action cycle, it has been assumed that optical variables which are useful for making discriminations between types of self-motion events would also influence an individual's action when made in order to control stimulation. By using an interactive paradigm, it has been possible to demonstrate that the optical variable previously identified as being useful for detecting changes in self motion (Owen et al., 1981; Tobias, 1983; Tobias & Owen, 1984) also influenced the participants' action as they attempted to counter a forcing function and maintain a constant velocity. The results showed that as the change in the rate of self motion became easier to detect, the actions intended to cancel the change became more accurate.

Prior investigations of optical variables, using a reactive methodology, have been successful in operationally distinguishing contextual variables from functional variables on the basis of the characteristic psychophysical functions that were produced. However, the inherent limitations of the reactive methodology preclude its use in the identification of the effects of contextual variables on the actions which are produced in order to control stimulation. The interactive methodology used in this experiment, in contrast, was capable of illustrating the consequences of inappropriately using what should have been a contextual variable as though it were functional information, for the task of detecting and controlling changes in the rate of self motion. Rather than producing the optimizing function for sensitivity to changes in self motion that had previously been observed (Tobias & Owen, 1984) when an irrelevant variable is inappropriately attended to as relevant information, increasing the magnitude of that variable apparently has the effect of decreasing the accuracy of the actions intended to control stimulation. The present investigation has revealed that the optical information that was typically treated as a contextual variable was mistakenly used as though it were functional information, with deleterious effects to performance.

This observation motivates several intriguing questions: (a) What specific characteristics of the irrelevant aspect of stimulation lead to its being mistakenly used as functional information for a particular task? (b) What are the specific event or task parameters that lead to a particular irrelevant aspect of stimulation being mistakenly used as functional information? (c) What training techniques can be used to educate the attention of an individual to the difference between relevant and irrelevant information? Although all three questions can be addressed with further application of an interactive methodology, some answers to the third question have already been discussed herein. Because the participants were able to see when their performance was in error and make adaptive adjustments in their control of stimulation during the ongoing event, substantial improvements in performance were observed. Additional research is, however, needed in order to develop techniques by which interactive conditions can be used to better facilitate training in a variety of control tasks.

APPENDIX III-A: INVENTORY OF FLIGHT AND GROUND TEXTURE PARAMETERS

Table III-A-1. Inventory of Flight Parameters[a]

Filename	SR	ETime	PTime	z	$\dot{z}$	$\ddot{z}$	$R_{\dot{z}}$	$\dot{x}_o$	$\ddot{x}_t$	$R_{\dot{x}}$
020001.DAC	30	10.0	0.0	12.0	0	0	1	192	-12.288	1.0
020002.DAC	30	10.0	0.0	12.0	0	0	1	192	-15.360	1.0
020003.DAC	30	10.0	0.0	12.0	0	0	1	192	-19.200	1.0
020004.DAC	30	10.0	0.0	12.0	0	0	1	192	12.288	1.0
020005.DAC	30	10.0	0.0	12.0	0	0	1	192	15.360	1.0
020006.DAC	30	10.0	0.0	12.0	0	0	1	192	19.200	1.0
020007.DAC	30	10.0	0.0	24.0	0	0	1	192	-12.288	1.0
020008.DAC	30	10.0	0.0	24.0	0	0	1	192	-15.360	1.0
020009.DAC	30	10.0	0.0	24.0	0	0	1	192	-19.200	1.0
020010.DAC	30	10.0	0.0	24.0	0	0	1	192	12.288	1.0
020011.DAC	30	10.0	0.0	24.0	0	0	1	192	15.360	1.0
020012.DAC	30	10.0	0.0	24.0	0	0	1	192	19.200	1.0
020013.DAC	30	10.0	0.0	48.0	0	0	1	192	-12.288	1.0
020014.DAC	30	10.0	0.0	48.0	0	0	1	192	-15.360	1.0
020015.DAC	30	10.0	0.0	48.0	0	0	1	192	-19.200	1.0
020016.DAC	30	10.0	0.0	48.0	0	0	1	192	12.288	1.0
020017.DAC	30	10.0	0.0	48.0	0	0	1	192	15.360	1.0
020018.DAC	30	10.0	0.0	48.0	0	0	1	192	19.200	1.0

Table III-A-1 (Continued)

Note. A dot over a symbol indicates a derivative with respect to time. A subscript of zero indicates the value of a variable at the initiation of an event, whereas a subscript of t indicates the value of a variable at any time during the event.

[a]Parameters

SR = sampling rate

ETime = event duration(s)

PTime = preview period duration(s)

z = altitude (m)

$\dot{z}$ = climb rate (m/s)

$\ddot{z}$ = climb rate acceleration (m/s^2)

$R_{\dot{z}}$ = exponential rate of change in altitude (%/s)

$\dot{x}_o$ = initial forward velocity (m/s)

$\ddot{x}$ = acceleration rate (m/s^2)

$R_{\dot{x}}$ = exponential rate of change in velocity (%/s)

Table III-A-2.

Inventory of Ground-Texture Parameters[a]

Filename	X_g	Y_g
020001.TEX	6.0	24.0
020002.TEX	12.0	24.0
020003.TEX	24.0	24.0
020004.TEX	48.0	24.0
020005.TEX	96.0	24.0
020006.TEX	192.0	24.0

[a] Parameters

X_g = ground-texture dimension in the direction parallel to the direction of travel (m).

Y_g = ground-texture dimension in the direction perpendicular to the direction of travel (m).

APPENDIX III-B: INVENTORY OF EVENT AND PERFORMANCE VARIABLES

Table III-B-1. Inventory of Event Variables[a]

Event number	1 $(\dot{x}/x_g)$	2 $(\dot{x}/z)$	3 $(\ddot{x}/\dot{x})$	4 $(\ddot{x}/x_g)$	5 $(\ddot{x}/z)$	6 (z/x_g)	7 x_g	8 $\ddot{x}$	9 z
1	1	4	.064	.064	.256	.250	192	12.3	48
2	1	4	.080	.080	.320	.250	192	15.4	48
3	1	4	.100	.100	.400	.250	192	19.2	48
4	1	8	.064	.064	.512	.125	192	12.3	24
5	1	8	.080	.080	.640	.125	192	15.4	24
6	1	8	.100	.100	.800	.125	192	19.2	24
7	1	16	.064	.064	1.024	.0625	192	12.3	12
8	1	16	.080	.080	1.280	.0625	192	15.4	12
9	1	16	.100	.100	1.600	.0625	192	19.2	12
10	2	4	.064	.128	.256	.500	96	12.3	48
11	2	4	.080	.160	.320	.500	96	15.4	48
12	2	4	.100	.200	.400	.500	96	19.2	48
13	2	8	.064	.128	.512	.250	96	12.3	24
14	2	8	.080	.160	.640	.250	96	15.4	24
15	2	8	.100	.200	.800	.250	96	19.2	24
16	2	16	.064	.128	1.024	.125	96	12.3	12
17	2	16	.080	.160	1.280	.125	96	15.4	12
18	2	16	.100	.200	1.600	.125	96	19.2	12
19	4	4	.064	.256	.256	1.000	48	12.3	48
20	4	4	.080	.320	.320	1.000	48	15.4	48

Table III-B-1 (Continued)

Event number	1 ($\dot{x}/x_g$)	2 ($\dot{x}/z$)	3 ($\ddot{x}/\dot{x}$)	4 ($\ddot{x}/x_g$)	5 (x/z)	6 (z/x_g)	7 x_g	8 $\ddot{x}$	9 z
21	4	4	.100	.400	.400	1.000	48	19.2	48
22	4	8	.064	.256	.215	.500	48	12.3	24
23	4	8	.080	.320	.640	.500	48	15.4	24
24	4	8	.100	.400	.800	.500	48	19.2	24
25	4	16	.064	.256	1.024	.250	48	12.3	12
26	4	16	.080	.320	1.280	.250	48	15.4	12
27	4	16	.100	.400	1.600	.250	48	19.2	12
28	8	4	.064	.512	.256	2.000	24	12.3	48
29	8	4	.080	.640	.320	2.000	24	15.4	48
30	8	4	.100	.800	.400	2.000	24	19.2	48
31	8	8	.064	.512	.512	1.000	24	12.3	24
32	8	8	.064	.640	.640	1.000	24	15.4	24
33	8	8	.100	.800	.800	1.000	24	19.2	24
34	8	16	.064	.512	1.024	.500	24	12.3	12
35	8	16	.080	.640	1.280	.500	24	15.4	12
36	8	16	.100	.800	1.600	.500	24	19.2	12
37	16	4	.064	1.024	.256	4.000	12	12.3	48
38	16	4	.080	1.280	.320	4.000	12	15.4	48
39	16	4	.100	1.600	.400	4.000	12	19.2	48
40	16	8	.064	1.024	.512	2.000	12	12.3	24
41	16	8	.080	1.280	.640	2.000	12	15.4	24
42	16	8	.100	1.600	.800	2.000	12	19.2	24

Table III-B-1 (Continued)

Event number	1 $(\dot{x}/x_g)$	2 $(\dot{x}/z)$	3 $(\ddot{x}/\dot{x})$	4 $(\ddot{x}/x_g)$	5 $(\ddot{x}/z)$	6 (z/x_g)	7 x_g	8 $\ddot{x}$	9 z
43	16	16	.064	1.024	1.024	1.000	12	12.3	12
44	16	16	.080	1.280	1.280	1.000	12	15.4	12
45	16	16	.100	1.600	1.600	1.000	12	19.2	12
46	32	4	.064	2.048	.256	8.000	6	12.3	48
47	32	4	.080	2.560	.320	8.000	6	15.4	48
48	32	4	.100	3.200	.400	8.000	6	19.2	48
49	32	8	.064	2.048	.512	4.000	6	12.3	24
50	32	8	.080	2.560	.640	4.000	6	15.4	24
51	32	8	.100	3.200	.800	4.000	6	19.2	24
52	32	16	.064	2.048	1.024	2.000	6	12.3	12
53	32	16	.080	2.560	1.280	2.000	6	15.4	12
54	32	16	.100	3.200	1.600	2.000	6	19.2	12

Note. A dot over a symbol indicates a derivative with respect to time. A subscript of zero indicates the value of a variable at the initiation of an event, whereas the absence of a subscript indicates the value of a variable at any time during the event. The initial speed $(\dot{x})$ = 192 m/s for all events.

Table III-B-1 (Concluded)

Variables

1. $(\dot{x}/xg)$ = initial edge rate (in edges/sec).

2. $(\dot{x}/z)$ = initial global optical flow rate (in eyeheights/sec).

3. $(\ddot{x}/\dot{x})$ = initial fractional change in flow rate, edge rate, and speed (in %/sec). Add negative sign for deceleration trials.

4. $(\ddot{x}/x_g)$ = initial change in edge rate (in edges/sec^2).

5. $(\ddot{x}/z)$ = initial change in flow rate (in eyeheights/sec^2).

6. (z/x_g) = global optical density (in ground units/eyeheight).

7. x_g = ground-texture-unit size in the dimension parallel to the direction of travel (in meters).

8. $\ddot{x}$ = change in speed (meters/sec^2).

9. z = altitude (in meters).

Table III-B-2. Inventory of Performance Variables[a]

Event number	1 Err_{wd}	2 $\overline{RT}_c$	3 Ramp slope	4 $\dot{x}_m$	5 $\dot{x}_{sd}$	6 $\ddot{x}_m$	7 $\ddot{x}_{sd}$
			Acceleration				
1	.282	4.97	-1.73	244	8.78	-2.24	6.30
2	.232	5.11	-2.01	262	8.12	-1.19	3.60
3	.218	4.73	-2.08	283	11.18	-0.25	6.63
4	.148	4.55	-2.22	228	11.09	-5.17	6.89
5	.085	4.50	-2.27	247	11.00	-5.23	6.91
6	.197	4.40	-2.36	269	10.44	-1.60	7.20
7	.176	4.45	-2.46	217	15.34	-8.98	8.54
8	.169	4.22	-2.72	231	14.84	-7.75	7.85
9	.120	3.79	-2.73	243	16.07	-6.03	8.23
10	.261	5.04	-1.72	252	8.64	-1.40	5.20
11	.225	4.79	-1.79	260	9.65	-1.80	5.77
12	.169	4.84	-1.89	285	10.33	-0.44	5.57
13	.120	4.24	-1.88	227	12.07	-5.70	6.89
14	.162	4.14	-2.31	246	10.62	-3.78	6.55
15	.092	4.08	-2.46	262	13.18	-2.10	7.24
16	.099	3.85	-2.34	206	17.86	-8.40	8.22
17	.106	3.47	-2.63	218	16.68	-7.34	8.45
18	.120	3.48	-2.88	233	17.77	-7.24	8.40
19	.169	4.71	-1.93	238	9.46	-4.39	5.29

Table III-B-2 (Continued)

Event	1	2	3	4	5	6	7
number	Err_{wd}	$\overline{RT}_c$	Ramp slope	$\dot{x}_m$	$\dot{x}_{sd}$	$\ddot{x}_m$	$\ddot{x}_{sd}$
20	.169	5.38	-1.77	279	8.91	-0.83	5.27
21	.127	5.05	-2.14	291	10.52	-1.45	5.73
22	.218	5.13	-2.02	241	9.38	-4.93	7.11
23	.156	3.94	-2.24	246	10.17	-1.45	6.07
24	.070	4.29	-2.37	269	10.22	-1.89	6.45
25	.148	3.55	-2.27	211	14.42	-6.62	7.24
26	.120	3.31	-2.48	221	15.65	-6.12	8.83
27	.049	3.34	-2.95	238	14.85	-5.09	7.62
28	.261	5.42	-2.08	247	9.73	-3.81	5.73
29	.176	4.78	-1.78	260	8.91	-2.47	5.65
30	.190	4.91	-2.02	289	9.87	-1.29	5.03
31	.190	4.98	-1.97	237	10.57	-5.54	6.83
32	.169	4.44	-2.05	243	10.67	-5.07	5.88
33	.106	4.13	-2.62	266	11.37	-292	5.60
34	.155	3.56	-2.08	211	14.64	-6.79	7.90
35	.134	3.38	-2.59	217	16.07	-7.49	7.43
36	.106	3.37	-2.70	242	13.62	-4.69	7.91
37	.225	5.40	-2.11	246	9.53	-5.79	4.84
38	.176	5.51	-1.78	272	8.66	-2.97	5.03
39	.176	5.27	-1.81	295	8.17	-0.47	4.69
40	.197	5.01	-1.97	236	12.46	-7.08	6.42
41	.197	4.80	-2.17	261	11.79	-3.34	6.67

Table III-B-2 (Continued)

Event number	1 Err_{wd}	2 $\overline{RT}_c$	3 Ramp slope	4 $\dot{x}_m$	5 $\dot{x}_{sd}$	6 $\ddot{x}_m$	7 $\ddot{x}_{sd}$
42	.169	5.17	-2.20	285	10.34	-2.14	5.74
43	.120	3.52	-2.34	204	17.77	-8.30	8.77
44	.148	4.08	-2.63	226	16.24	-8.12	8.24
45	.070	2.81	-2.85	223	16.64	-6.26	8.65
46	.225	4.99	-1.83	245	11.52	-2.79	5.94
47	.239	5.39	-2.01	270	7.89	-2.85	4.22
48	.162	5.13	-1.89	289	10.85	-1.23	5.42
49	.169	4.69	-2.17	231	13.30	-7.03	7.22
50	.211	5.33	-2.28	261	11.84	-5.79	6.21
51	.155	4.42	-2.31	268	13.77	-4.76	6.39
52	.127	3.49	-2.43	197	20.88	-10.20	8.21
53	.120	3.40	-2.49	213	19.25	-7.93	8.83
54	.085	3.01	-3.09	220	21.55	-8.03	9.13
			Deceleration				
1	.070	3.67	2.70	183	18.5	10.51	7.61
2	.056	3.31	2.90	174	18.8	9.55	8.12
3	.035	3.12	3.38	161	19.3	8.94	8.24
4	.049	3.51	2.90	183	16.9	9.00	8.25
5	.042	3.47	3.66	173	17.0	8.73	8.98
6	.077	3.43	3.77	151	14.6	6.42	8.92

Table III-B-2 (Continued)

Event number	1 Err_{wd}	2 $\overline{RT}_c$	3 Ramp slope	4 $\dot{x}_m$	5 $\dot{x}_{sd}$	6 $\ddot{x}_m$	7 $\ddot{x}_{sd}$
7	.077	3.39	2.78	179	15.4	6.83	8.16
8	.042	3.30	3.15	168	15.8	6.12	8.13
9	.099	3.33	3.65	150	13.9	5.05	8.64
10	.056	3.57	2.63	181	17.8	9.66	7.62
11	.035	3.42	3.03	174	19.5	9.52	7.91
12	.063	3.32	3.25	156	16.9	7.69	8.76
13	.099	3.76	2.86	176	14.8	7.28	8.47
14	.106	3.42	3.28	168	15.3	7.35	8.36
15	.049	3.20	3.63	150	12.9	4.58	8.68
16	.134	3.60	3.10	178	15.6	7.22	10.21
17	.141	3.56	3.65	161	12.9	4.51	9.68
18	.106	3.38	3.41	146	12.2	3.92	9.71
19	.035	3.91	3.05	179	17.1	9.80	7.76
20	.021	3.97	3.26	163	16.4	9.06	8.44
21	.085	3.02	3.04	164	18.7	8.26	7.66
22	.099	4.39	2.63	165	12.7	7.08	8.57
23	.106	3.66	2.91	157	12.2	5.34	7.93
24	.028	2.94	2.98	165	16.8	7.22	8.38
25	.218	4.37	2.94	163	11.7	6.93	8.87
26	.141	3.38	3.47	170	14.7	6.54	9.97
27	.134	3.22	4.12	150	11.9	3.76	9.06
28	.070	3.91	2.77	175	15.3	8.50	7.71

Table III-B-2 (Continued)

Event number	1 Err_{wd}	2 $\overline{RT}_c$	3 Ramp slope	4 $\dot{x}_m$	5 $\dot{x}_{sd}$	6 $\ddot{x}_m$	7 $\ddot{x}_{sd}$
29	.042	3.59	3.03	163	15.5	7.39	7.48
30	.070	3.40	3.37	150	13.2	5.68	7.33
31	.077	3.94	2.89	168	12.9	6.28	8.62
32	.099	3.38	2.88	166	13.1	5.80	7.95
33	.077	3.15	3.71	159	14.5	6.16	9.11
34	.099	4.12	2.83	166	11.9	6.01	9.26
35	.141	3.33	3.48	174	15.7	6.90	9.75
36	.204	3.01	3.56	156	13.1	4.29	9.21
37	.042	3.74	2.66	180	17.6	9.70	6.77
38	.063	3.20	2.95	175	16.5	8.15	7.77
39	.063	3.03	3.25	157	15.5	6.22	7.37
40	.162	4.06	3.11	176	15.1	8.71	8.49
41	.056	3.58	3.29	161	12.7	5.42	9.00
42	.120	3.34	3.79	152	13.4	5.21	9.05
43	.169	4.02	3.26	171	13.2	6.42	9.45
44	.204	3.42	3.75	164	13.0	5.38	8.79
45	.204	3.08	3.65	151	12.7	3.18	9.91
46	.021	4.10	2.61	171	14.7	8.26	7.32
47	.049	3.60	3.20	163	15.3	7.39	6.72
48	.049	3.56	2.68	146	15.1	6.86	7.88
49	.127	3.87	3.24	181	16.4	9.50	8.95
50	.092	4.20	2.85	150	12.5	6.41	8.00

Table III-B-2 (Concluded)

Event number	1 Err_{wd}	2 $\overline{RT_c}$	3 Ramp slope	4 $\dot{x}_m$	5 $\dot{x}_{sd}$	6 $\ddot{x}_m$	7 $\ddot{x}_{sd}$
51	.176	3.66	4.03	146	13.3	5.99	8.03
52	.225	4.10	2.89	167	13.7	2.59	9.06
53	.211	3.89	3.01	155	13.5	6.03	10.08
54	.232	3.44	4.01	142	12.6	3.08	9.65

Note. A dot over a symbol indicates a derivative with respect to time.

[a]Variables

1. Event number corresponds to the event number on the inventory of event variables.

2. Err_{wd} - Proportion error in direction of initial response (wrong direction).

3. $\overline{RT_c}$ - Mean correct reaction time (s).

4. Ramp slope - Slope of the initial corrective response - x (m/s^3).

5. $\dot{x}_m$ - Mean velocity produced during maintenance phase of performance (m/s).

6. $\dot{x}_{sd}$ - Standard deviation in velocity produced during maintenance phase of performance (m/s).

7. $\ddot{x}_m$ - Mean acceleration produced during maintenance phase of performance (m/s^2).

8. $\ddot{x}_{sd}$ - Standard deviation in acceleration produced during maintenance phase of performance (m/s^2).

APPENDIX III-C: INSTRUCTIONS

INSTRUCTIONS FOR INTERACTIVE FLIGHT SIMULATION: VELOCITY CONTROL

Welcome to the Aviation Psychology Laboratory. We are presently conducting research to assess the relative influences of various visual factors on your ability to control simulated self motion. We want to determine how well you can visually detect and control changes in simulated forward motion in the absence of actual movement or vibration which typically accompanies self motion.

Each trial will consist of a computer-generated event on the screen which represents forward travel in an airplane over open flat fields. The initial speed is the same on all trials. Your task is to maintain a constant forward speed at all times. On each trial you will encounter either a head wind or a tail wind which will cause your speed to either decrease or increase. As soon as you detect a decrease or an increase in speed, adjust the control by applying an appropriate force in the appropriate direction, so that you can cancel the change and maintain a constant speed.

The stick controls the speed of simulated flight by increasing your speed if you push the stick forward, or decreasing your speed if you pull back on the stick. The force control, identical to those currently used in high performance aircraft, electronically records the amount of force that you apply while either gently pushing or pulling on the stick. The stick itself will not actually move the way your gas or brake pedal does when you apply a force to it in order to change the speed of your car. You will therefore be given four 10-second practice trials at the beginning of each test session. The first two practice trials are designed so that you may become acquainted with the force control and the dynamics of your simulated flight. On these first two trials, the only change in speed that will occur is the change that you cause with the control stick. The third practice trial will simulate a loss in speed, and the fourth practice trial will simulate a gain in speed. The remaining events will be a random sequence of test trials in which you are required to detect a change in speed, and apply force that will counter the change, so that your flight is at a constant speed.

The specific procedure is as follows:

1. Before the beginning of each event, you will hear a "beep" in the headset; at that time, turn your full attention to the screen.
2. Remember, you are required to maintain a constant speed, so as soon as you detect a change in your speed, you must correct it by applying a force to counter the changing speed in order to maintain a constant forward speed as well as you can for the remainder of the trial.
3. If you notice that you are slowing down, you should push the stick forward in order to increase you speed. If you notice that you are speeding up, you should pull the stick back in order to decrease your speed. Do not touch the control stick until you detect a change in speed, since it is very sensitive to any force that you apply.
4. The experiment consists of 112 trials, including the four practice trials at the beginning of each test session. During the first two practice trials, you are to become acquainted with the dynamics of the force control stick. The third practice trial will simulate a decrease in forward speed, and the fourth practice trial will simulate an increase in forward speed.

Do you have any questions?

If you have any questions about the procedure during the practice trials, you should feel free to ask.

APPENDIX III-D: ANALYSIS OF VARIANCE SUMMARY TABLES

Table III-D-1. Analyses of Variance for All Events

Source	df	SS	$R^2\%$	F	$p<F$	$p_g<F$
		Error				
Session (S)	3	7.60	.52	6.43	.0006	.0026
Initial flow rate (F)	2	0.28	.02	.78	.4616	.4440
Initial edge rate (E)	4	1.74	.12	3.82	.0059	.0113
FE	8	2.50	.17	3.09	.0025	.0068
SFE	24	3.64	.25	1.63	.0298	.0948
Direction (D)	1	12.73	.87	10.73	.0027	-
FD	2	20.15	1.37	24.70	.0000	.0000
SFD	6	1.77	.12	2.78	.0132	.0298
ED	4	2.82	.19	3.90	.0037	.0132
SED	12	4.10	.28	3.90	.0000	.0000
FED	8	2.71	.18	3.22	.0017	.0090
Initial fractional change (C)	2	.27	.04	2.41	.0985	.1085
DC	2	.81	.11	9.29	.0003	.0003
FEDC x group	80	10.30	.70	1.47	.0082	.0360
Pooled error	12439	1397.30				
Total	12600	1468.72				

Table III-D-1 (Continued)

Source	df	SS	R^2%	F	p<F	p_g<F
		Reaction Time				
Session (S)	3	67.88	.12	.93		
Initial flow rate (F)	2	1651.53	2.84	77.75	.0000	.0000
SF	6	65.05	.11	4.22	.0005	.0023
Initial edge rate (E)	4	271.42	.47	11.04	.0000	.0001
SE	12	94.63	.16	4.47	.0000	.0001
FE	8	339.67	.58	16.78	.0000	*
Direction (D)	1	3106.30	5.34	49.80	.0000	-
SD	3	96.58	.17	5.90	.0010	.0031
FD	2	1264.71	2.17	75.03	.0000	.0000
SFD x Group (G)	30	116.10	.20	1.57	.0388	.0771
ED	4	134.42	.23	6.69	.0001	.0017
SED	12	65.47	.11	2.81	.0011	.0054
FED	8	181.63	.31	8.72	.0000	*
Initial fractional change (C)	2	404.71	.70	59.94	.0000	.0000
FC	4	29.37	.05	3.60	.0084	.0140
SFC	12	48.26	.08	1.99	.0245	.0568
EC	8	90.53	.16	4.93	.0000	*
SFECG	240	523.23	.90	1.34	.0012	.0340
FEDC	16	57.54	.10	1.76	.0345	*
FEDCG	80	217.89	.37	1.33	.0393	*

Table III-D-1 (Continued)

Source	df	SS	R^2%	F	p<F	p_g<F
Pooled error	12143	49325.87				
Total	12600	58152.85				
		Ramp Slope				
Session (S)	3	592.38	.83	10.28	.0000	.0002
Initial flow rate (F)	2	530.34	.74	37.49	.0000	.0000
Initial edge rate (E)	4	40.81	.06	1.92	.1124	.1276
SE	12	79.52	.11	1.81	.0459	*
Direction (D)	1	2562.11	3.58	99.51	.0000	-
FD	2	163.17	.23	18.73	.0000	.0000
SFED	24	150.62	.21	1.73	.0164	.0648
Initial fractional change (C)	2	423.44	.59	32.34	.0000	.0000
SC x Group	30	222.38	.31	1.65	.0248	.0417
SEC	24	136.81	.19	1.75	.0151	*
FEC	16	142.56	.20	2.39	.0019	*
DC	2	35.70	.05	6.47	.0029	*
Pooled error	12478	66565.16				
Total	12600	71645.00				

Table III-D-1 (Concluded)

Note. Each effect was tested using the appropriate error term given by the model. Main effects are reported without regard to the level of significance, but only interactions significant at the $p < .05$ level or better have been included. Greenhouse-Geisser connected probabilities $P_g < F$ have been included due to violations in the assumptions of homogeneity of covariance. An asterisk (*) indicates that the assumption was not violated.

Table III-D-2. Analyses of Variance for Accelerating Events

Source	df	SS	R^2%	F	p<F	p_g<F
		Mean Velocity				
Session (S)	3	25584.62	.18	1.02	.3888	.3568
Initial flow rate (F)	2	2823608.53	19.83	142.96	.0000	.0000
SF	6	38787.78	.27	3.94	.0011	.0129
SF x Group (G)	30	94196.91	.66	1.92	.0057	.0377
Initial edge rate (E)	4	80048.94	.56	3.74	.0069	.0424
SE	12	77380.55	.54	5.73	.0000	.0000
FE	8	167610.75	1.18	11.31	.0000	.0000
Initial fractional change (C)	2	818269.60	5.75	333.53	.0000	.0000
FC	4	41839.14	.29	8.21	.0000	*
SFCG	60	62076.70	.43	1.44	.0248	*
EC	8	38579.69	.27	4.78	.0000	.0003
ECG	40	62083.58	.44	1.54	.0287	.0575
FEC	16	35128.38	.25	1.74	.0375	.0787
SFECG	240	274637.33	1.93	1.35	.0008	.0320
Pooled error	5865	9600384.20	4.20			
Total	6300	14240216.70				

Table III-D-2 (Continued)

Source	df	SS	R^2%	F	p<F	P_g<F
		Mean Flow Rate				
Session (S)	3	86.77	.04	1.23	.3062	.2994
Initial flow rate (F)	2	150263.77	71.64	1445.57	.0000	.0000
SF	6	135.45	.06	2.77	.0138	.0608
Initial edge rate (E)	4	284.28	.14	4.47	.0022	.0262
SE	12	189.50	.09	4.79	.0000	.0001
FE	8	717.77	.34	11.63	.0000	.0000
Initial fractional change (C)	2	1618.81	.77	232.05	.0000	.0000
FC	4	250.21	.12	18.28	.0000	.0000
SFC	12	54.49	.02	2.01	.0232	.0775
EC	8	101.20	.05	4.16	.0001	.0013
SEC x Group (G)	120	392.22	.19	1.29	.0305	.0991
FEC	16	116.42	.06	1.89	.0195	.0783
SFECG	240	775.66	.37	1.22	.0212	.1410
Pooled error	5863	54753.03				
Total	6300	209739.58				
		Mean Edge Rate				
Session (S)	3	329.37	.02	2.92	.0394	.0728
Initial flow rate (F)	2	14282.39	1.00	113.10	.0000	.0000
SF	6	159.88	.01	2.65	.0179	.0516
Initial edge rate (E)	4	1231450.03	86.40	2983.54	.0000	.0000
SE	12	507.14	.04	2.90	.0008	.0507

Table III-D-2 (Continued)

Source	df	SS	$R^2\%$	F	$p<F$	$p_g<F$
FE	2	3282.74	.23	196.21	.0000	.0000
FC	4	257.97	.02	6.01	.0002	.0003
SFC	60	533.53	.04	1.42	.0301	.0607
EC	8	3326.92	.23	48.04	.0000	.0000
EC x Group (G)	40	703.50	.05	2.03	.0007	.0231
FEC	16	469.23	.03	2.89	.0002	.0135
SFECG	240	2009.02	.14	1.19	.0357	.1917
Pooled error	5895	151064.16				
Total	6300	1425240.10				
		Mean Acceleration				
Session (S)	3	1468.51	.16	.86	.4680	.4083
Initial flow rate (F)	2	80401.88	8.51	88.53	.0000	.0000
SF	6	2243.66	.24	2.69	.0162	.0575
SF x Group (G)	30	7782.68	.82	1.87	.0076	.0462
Initial edge rate (E)	4	1756.93	.19	1.66	.1638	.2062
FE	8	4020.17	.42	3.58	.0007	.0037
SFE	24	3740.74	.40	1.97	.0040	.0351
SFEG	120	13239.38	1.40	1.39	.0067	.0499
Initial fractional change (C)	2	3882.42	.41	13.13	.0000	*
EC	8	1995.84	.21	2.88	.0046	*
ECG	40	5042.08	.53	1.46	.0487	*
SFECG	240	21231.49	2.25	1.25	.0101	.0992

Table III-D-2 (Continued)

Source	df	SS	$R^2\%$	F	p<F	p_g<F
Pooled error	5813	798255.07				
Total	6300	945060.85				
		Mean Flow Acceleration				
Session (S)	3	3.05	.12	.86	.4679	.4155
Initial edge rate (F)	2	335.27	13.64	89.04	.0000	.0000
Initial edge rate (E)	4	7.01	.28	2.63	.0385	.0936
FE	8	11.95	.49	3.94	.0002	.0038
Initial fractional change (C)	2	8.78	.36	13.77	.0000	*
EC	8	3.33	2.19	.14	.0291	*
SEC x Group (G)	120	30.40	1.31	1.23	.0241	.0942
SFECG	240	58.41	2.38	1.36	.0006	.0548
Pooled error	5913	1999.99				
Total	6300	2458.19				
		Mean Edge Rate Acceleration				
Session (S)	3	2.86	.04	.43	.7305	.6606
Initial flow rate (F)	2	320.16	4.23	54.48	.0000	.0000
SF	6	19.72	.26	3.97	.0010	.0057
SF x Group (G)	30	38.53	.50	1.55	.0452	.0847
Initial edge rate (E)	4	112.86	1.49	3.96	.0049	.0522

Table III-D-2 (Continued)

Source	df	SS	R^2%	F	p<F	p_g<F
FE	8	399.09	5.28	35.07	.0000	.0000
SFE	24	35.72	.47	2.27	.0005	.0319
Initial fractional change (C)	2	7.18	.10	3.25	.0468	*
FEC	16	40.57	.54	2.89	.0002	.0199
SFECG	240	171.02	2.26	1.19	.0344	.2032
Pooled error	5965	6416.65				
Total	6300	7564.36				
Mean Fractional Rate of Change						
Session (S)	3	0.02	.13	0.91	.4112	.3968
Initial flow rate (F)	2	1.39	7.43	73.45	.0000	.0000
Initial edge rate (E)	4	0.09	.48	3.41	.0116	.0533
Initial fractional change (C)	2	0.13	.71	15.62	.0000	.0001
Pooled error	6287	17.10				
Total	6300	18.73				
Standard Deviation in Velocity						
Session (S)	3	6789.01	.92	4.40	.0065	.0200
Initial flow rate (F)	2	27749.55	3.75	19.94	.0000	.0000
Initial edge rate (E)	4	4039.88	.55	6.23	.0002	.0006
FE	8	4750.23	.64	4.65	.0000	.0018
Initial fractional change (C)	2	576.73	.08	1.65	.2021	.2027
EC	8	2443.17	.33	3.64	.0006	.0022

Table III-D-2 (Continued)

Source	df	SS	$R^2\%$	F	$p<F$	$p_g<F$
FEC x Group (G)	80	9775.07	1.32	1.32	.0464	*
FEC x Group (G)	80	9775.07	1.32	1.32	.0464	*
SFECG	240	20612.88	2.78	1.18	.0425	.1504
Pooled error	5953	663852.06				
Total	6300	740588.58				
Standard Deviation in Flow Rate						
Session (S)	3	17.41	.46	5.15	.0027	.0091
Initial flow rate (F)	2	1570.59	41.83	273.59	.0000	.0000
SF	6	10.73	.29	3.98	.0010	.0082
Initial edge rate (E)	4	18.29	.49	10.94	.0000	.0000
FE	8	23.89	.64	8.93	.0000	.0000
Initial fractional change (C)	2	.94	.02	1.26	.2933	.3410
EC	8	5.07	.14	2.75	.0065	*
Pooled error	6267	2107.54				
Total	6300	3754.46				
Standard Deviation in Edge Rate						
Session (S)	3	32.36	.27	4.75	.0043	.0101
Initial flow rate (F)	2	161.89	1.36	17.40	.0000	.0001
Initial edge rate (E)	4	5468.10	46.00	327.60	.0000	.0000
SE	12	33.98	.18	2.71	.0017	.0434
FE	8	238.29	2.00	13.63	.0000	.0001
Initial fractional change (C)	2	10.32	.05	4.13	.0216	*

Table III-D-2 (Continued)

Source	df	SS	R^2%	F	$p<F$	$p_g<F$
SC x Group (G)	30	23.73	.13	1.57	.0406	*
EC	8	36.93	.20	5.27	.0000	*
SECG	120	90.19	.76	1.52	.0009	.0486
Pooled error	6111	5792.44				
Total	6300	11888.23				
Standard Deviation in Acceleration						
Session	3	3608.56	1.37	4.09	.0095	.0348
Initial flow rate (F)	2	7700.92	2.92	54.36	.0000	.0000
SF	6	406.85	.15	2.94	.0096	.0220
Initial edge rate (E)	4	394.54	.15	2.45	.0504	.0791
Initial fractional change (C)	2	19.69	.01	.55	.5819	.5270
Pooled error	6283	252038.03				
Total	6300	264168.59				
Standard Deviation in Flow Acceleration						
Session (S)	3	11.66	.86	4.83	.0039	.0184
Initial flow rate (F)	2	419.82	30.94	150.91	.0000	.0000
SF	6	7.25	.53	5.46	.0000	.0000
Initial edge rate (E)	4	.60	.04	1.05	.3835	.3694
SE	12	2.26	.17	2.16	.0133	.0378
SFE	24	3.18	.23	1.73	.0166	.0850
Initial fractional change (C)	2	.10	.01	.70	.5009	.4828

Table III-D-2 (Continued)

Source	df	SS	R^2%	F	$p<F$	$p_g<F$
Pooled error	6247	911.84				
Total	6300	1356.71				
Standard Deviation in Edge Acceleration						
Session (S)	3	18.26	.56	4.91	.0036	.0137
Initial flow rate (F)	2	37.01	1.13	40.41	.0000	.0000
SF	6	3.57	.11	3.37	.0037	.0098
Initial edge rate (E)	4	1204.12	36.66	132.52	.0000	.0000
SE	12	16.87	.51	3.17	.0003	.0302
FE	8	36.14	1.10	12.46	.0000	.0000
SFE	24	7.33	.22	1.60	.0357	.1443
Initial fractional change (C)	2	.61	.11	1.66	.2010	.2055
SFC x Group (G)	60	17.32	.53	1.67	.0030	.0164
SECG	120	25.58	.78	1.26	.0454	.1764
FECG	80	26.56	.81	1.36	.0289	.1521
Pooled error	5979	1891.17				
Total	6300	3284.63				
Standard Deviation in Fractional Rate of Change						
Session (S)	3	.17	.01	.25	.8601	.6270
Initial flow rate (F)	2	.65	.03	.25	.7762	.6188
Initial edge rate (E)	4	2.65	.13	.53	.7142	.4736
Initial fractional change (C)	2	1.73	.09	.69	.5072	.4145

Table III-D-2 (Concluded)

Source	df	SS	$R^2\%$	F	p<F	p_g<F
Pooled error	6289	1997.92				
Total	6300	2003.12				

Note. Each effect was tested using the appropriate error term given by the model. Main effects are reported without regard to the level of significance, but only interactions significant at the $p < .05$ level or better have been included. Greenhouse-Geisser connected probabilities $P_g < F$ have been included due to violations in the assumptions of homogeneity of covariance. An asterisk (*) indicates that the assumption was not violated.

Table III-D-3. Analyses of Variance for Decelerating Events

Source	df	SS	R^2%	F	$p<F$	$p_g<F$
		Mean Velocity				
Between Subjects						
Group (G)	5	1143579.31	13.0	5.31	.0014	-
Within Subjects						
Session (S)	3	123669.30	1.42	8.02	.0001	.0007
Initial flow rate (F)	2	125410.92	1.44	10.83	.0001	.0015
SF	6	22179.51	.25	2.47	.0256	.0801
Initial edge rate (E)	4	175034.86	2.00	15.33	.0000	.0000
SE	12	45306.20	.52	5.12	.0000	.0000
FE	8	30791.08	.35	4.04	.0002	.0032
SFE	24	25070.56	.29	1.75	.0154	.0579
SFEG	120	104577.48	1.20	1.46	.0023	.0224
Initial fractional change (C)	2	545261.82	6.24	355.17	.0000	.0000
CG	10	16774.26	.19	2.18	.0318	.0435
SCG	30	24954.55	.29	1.62	.0305	.0476
SFC	12	11185.07	.13	1.86	.0769	.0424
EC	8	31416.12	.36	6.71	.0000	.0000
SECG	120	80821.32	.93	1.30	.0261	.0879
FEC	16	47974.18	.55	5.06	.0000	.0000
SFECG	240	153857.39	1.76	1.20	.0276	.1293
Pooled error	5678	6045251.16				
Total	6300	8733169.78				

Table III-D-3 (Continued)

Source	df	SS	R^2%	F	$p<F$	$p_g<F$
Mean Flow Rate						
Between Subjects						
Group (G)	5	2233.79	1.79	5.13	.0017	-
Within Subjects						
Session (S)	3	372.70	.30	11.07	.0000	.0000
Initial flow rate (F)	2	97507.27	77.96	2454.50	.0000	.0000
SF	6	216.53	.17	8.09	.0000	.0000
Initial edge rate (E)	4	469.06	.38	12.23	.0000	.0001
SE	12	134.84	.11	4.99	.0000	.0000
FE	8	248.75	.20	6.41	.0000	.0016
SFE	24	111.53	.09	2.41	.0002	.0131
SFEG	120	341.38	.27	1.48	.0016	.0351
Initial fractional change (C)	2	1262.07	1.00	336.59	.0000	.0000
CG	10	42.26	.03	2.25	.0266	.0419
SCG	30	76.31	.06	1.53	.0497	.0753
FC	4	363.23	.29	52.80	.0000	.0000
SFC	12	34.90	.03	1.82	.0437	.1122
SFCG	60	133.27	.11	1.39	.0380	.1178
EC	8	114.72	.09	8.26	.0000	.0000
ECG	40	107.73	.09	1.55	.0251	.0459
FEC	16	126.42	.10	4.66	.0000	.0000
Pooled error	5934	21168.41				
Total	6300	125065.15				

Table III-D-3 (Continued)

Source	df	SS	$R^2\%$	F	$p<F$	$p_g<F$
		Mean Edge Rate				
Between Subjects						
Group (G)	5	4356.98	.73	5.88	.0007	-
Within Subjects						
Session (S)	3	1025.59	.17	15.86	.0000	.0000
Initial flow rate (F)	2	667.97	.11	9.07	.0004	.0031
SF	6	149.77	.02	2.04	.0295	.0681
Initial edge rate (E)	4	517915.31	86.36	3242.23	.0000	.0000
SE	12	1553.67	.26	15.18	.0000	.0000
FE	8	975.30	.16	8.29	.0000	.0019
SFE	24	286.44	.05	1.89	.0065	.0916
SFEG	120	1254.84	.21	1.65	.0001	.0290
Initial fractional change (C)	2	2107.33	.35	155.78	.0000	*
FC	4	151.18	.02	7.63	.0000	*
EC	8	2623.18	.44	60.44	.0000	.0000
SECG	120	733.98	.12	1.36	.0106	.1098
FEC	16	416.28	.07	5.14	.0000	.0002
SFECG	240	1433.86	.24	1.37	.0005	.0570
Pooled error	5726	64100.25				
Total	6300	599751.93				
		Mean Acceleration				
Session (S)	3	886.98	.22	1.31	.2753	.2772

Table III-D-3 (Continued)

Source	df	SS	$R^2\%$	F	$p<F$	$p_g<F$
Initial flow rate (F)	2	15052.01	3.74	50.41	.0000	.0000
F x Group	10	3829.53	.95	2.56	.0122	.0288
SF	6	1086.91	.27	4.04	.0008	.0046
Initial edge rate	4	4032.24	1.00	11.67	.0000	.0000
SE	12	2019.84	.50	4.33	.0000	.0001
FE	8	968.29	.24	2.71	.0071	.0781
Initial fractional change (C)	2	4726.46	1.17	57.41	.0000	.0000
FEC	16	1495.13	.37	2.25	.0038	.0272
Pooled error	6237	368866.25				
Total	6300	402963.64				
Mean Flow Acceleration						
Session (S)	3	3.34	.28	2.19	.0947	.1111
Initial flow rate (F)	2	35.28	2.95	12.11	.0000	.0012
SF	6	4.34	.36	4.78	.0002	.0021
Initial edge rate (E)	4	8.72	.73	7.23	.0000	.0000
SE	12	5.73	.48	3.73	.0000	.0006
FE	8	4.24	.35	2.73	.0067	.0428
Initial fractional change (C)	2	12.12	1.01	40.52	.0000	.0000
FC	4	5.24	.44	10.22	.0000	.0000
FEC	16	3.86	.32	2.15	.0060	.0421
Pooled error	6243	1115.28				
Total	6300	1198.15				

Table III-D-3 (Continued)

Source	df	SS	R^2%	F	p<F	p_g<F
		Mean Edge Acceleration				
Session (S)	3	15.60	.39	5.42	.0018	.0051
Initial flow rate (F)	2	56.98	1.43	24.06	.0000	.0000
F x Group (G)	10	24.72	.62	2.09	.0401	.0705
SF	6	6.51	.16	3.08	.0068	*
Initial edge rate (E)	4	673.96	16.95	38.32	.0000	.0000
SE	12	35.05	.88	6.56	.0000	.0002
FE	8	62.10	1.56	11.81	.0000	.0001
FEG	40	43.17	1.09	1.64	.0132	.1281
Initial fractional change (C)	2	23.10	.58	42.07	.0000	.0000
SC	6	4.57	.11	2.55	.0215	.0333
FC	4	3.17	.08	2.69	.0344	*
SFC	12	6.23	.16	1.89	.0340	.0767
EC	8	25.56	.64	12.21	.0000	.0000
SEC	24	15.70	.39	2.41	.0002	.0250
FEC	16	8.50	.21	1.69	.0447	.1520
SFEC	48	17.81	.45	1.41	.0362	.1928
Pooled error	6095	2953.49				
Total	6300	3976.22				

Table III-D-3 (Continued)

Source	df	SS	R^2%	F	$p<F$	$p_g<F$
Mean Fractional Rate of Change						
Session (S)	3	0.05	.19	1.23	.3050	.3039
Initial flow rate (F)	2	0.48	1.89	34.57	.0000	.0000
Initial edge rate (E)	4	0.12	.48	5.26	.0006	.0027
SE	12	0.09	.34	2.18	.0122	.0610
Initial fractional change (C)	2	0.05	.20	6.85	.0021	*
FC	4	0.04	.15	3.43	.0108	.0191
SEC	24	0.10	.39	1.58	.0394	.1433
FEC	16	0.11	.42	2.00	.0118	.0742
Pooled error	6233	24.51				
Total	6300	25.55				
Standard Deviation in Velocity						
Session (S)	3	11793.90	1.65	7.10	.0003	.0025
Initial flow rate (F)	2	8068.26	1.13	12.37	.0000	.0004
F x Group (G)	10	6826.45	.95	2.09	.0396	.0694
Initial edge rate (E)	4	5801.69	.81	8.46	.0000	.0005
FE	8	2948.22	.41	5.64	.0000	*
Initial fractional change (C)	2	1044.61	.15	5.72	.0054	.0099
SC	6	965.11	.13	2.82	.0121	*
EC	8	1453.38	.20	2.72	.0069	*
FEC	16	2710.55	.39	2.79	.0003	.0043
SFECG	240	17236.02	2.41	1.31	.0024	.0482

Table III-D-3 (Continued)

Source	df	SS	R^2%	F	p<F	P_g<F
Pooled error	6001	656741.48				
Total	6300	715589.67				
Standard Deviation in Flow Rate						
Session (S)	3	27.04	1.01	7.46	.0002	.0012
Initial flow rate (F)	2	796.89	29.67	311.19	.0000	.0000
SF	6	11.05	.41	5.38	.0000	.0009
Initial edge rate (E)	4	8.08	.30	4.50	.0020	.0168
Initial fractional change (C)	2	2.53	.09	4.43	.0163	.0246
SC	6	2.31	.09	2.37	.0318	*
FC	4	2.93	.11	3.04	.0200	.0345
SFC x Group (G)	60	12.61	.47	1.36	.0474	.1181
EC	8	5.64	.21	3.65	.0005	*
FEC	16	8.33	.31	2.91	.0001	.0046
SFECG	240	54.78	2.04	1.32	.0019	.0830
Pooled error	5949	1753.62				
Total	6300	2685.81				

Table III-D-3 (Continued)

Source	df	SS	R^2%	F	$p<F$	$p_g<F$
Standard Deviation in Edge Rates						
Session (S)	3	32.15	.32	5.25	.0022	.0068
S x Group (G)	15	55.34	.55	1.81	.0460	.0738
Initial flow rate (F)	2	10.64	.11	2.84	.0666	.0822
SF	6	9.01	.09	2.41	.0288	.0481
Initial edge rate (E)	4	5028.87	49.82	256.80	.0000	.0000
SE	12	29.88	.30	3.18	.0003	.0186
FEG	40	53.61	.53	1.60	.0179	.1116
SFE	24	18.11	.18	1.60	.0357	.1503
Initial fractional change (C)	2	3.06	.03	2.16	.1245	.1266
FC	4	6.68	.07	3.61	.0083	*
EC	8	10.65	.11	2.51	.0324	.1084
SEC	24	17.43	.17	1.57	.0405	.1495
FEC	16	18.42	.18	2.65	.0005	.0237
Pooled error	6142	4810.16				
Total	6300	10093.37				
Standard Deviation in Acceleration						
Session (S)	3	4723.07	1.94	8.00	.0001	.0017
Initial flow rate (F)	2	6903.17	2.83	62.90	.0000	.0000
F x Group (G)	10	1483.64	.61	2.70	.0086	.0178
SFG	30	1070.66	.44	1.60	.0336	.0741
Initial edge rate (E)	4	215.96	.09	1.53	.1992	.2161

Table III-D-3 (Continued)

Source	df	SS	R^2%	F	p<F	P_g<F
SE	12	468.08	.19	1.83	.0417	.0807
FE	8	908.55	.37	6.30	.0000	*
Initial fractional change (C)	2	67.22	.03	1.55	.2202	.2236
FECG	80	2078.39	.85	1.37	.0251	.0724
Pooled error	6149	225844.52				
Total	6300	243763.26				
Standard Deviation in Flow Acceleration						
Session (S)	3	134.45	.97	8.05	.0001	.0016
Initial flow rate (F)	2	557.95	40.33	221.60	.0000	.0000
F x Group (G)	10	26.39	1.91	2.10	.0393	.0914
SF	6	6.19	.45	5.81	.0000	.0050
Initial edge rate (E)	4	2.03	.15	4.85	.0012	.0040
SE	12	1.78	.13	2.09	.0168	.0471
FE	8	4.19	.30	7.97	.0000	.0000
SFE	24	2.54	.18	1.59	.0371	.1344
Initial fractional change (C)	2	.10	.00	.62	.5414	.5152
Pooled error	6229	768.73				
Total	6300	1383.35				

Table III-D-3 (Continued)

Source	df	SS	$R^2\%$	F	$p<F$	$p_g<F$
Standard Deviation in Edge Acceleration						
Session (S)	3	21.44	.55	8.30	.0001	.0011
Initial flow rate (F)	2	43.95	1.13	53.05	.0000	.0000
Initial edge rate (E)	4	1952.26	49.96	210.71	.0000	.0000
SE	12	19.83	.51	5.50	.0000	.0000
FE	8	56.29	1.44	34.90	.0000	.0000
FE x Group (G)	40	12.81	.33	1.59	.0194	.1096
Initial fractional change (C)	2	.56	.00	1.50	.2319	.2327
FEC	16	4.01	.10	1.83	.0255	.1072
FECG	80	15.80	.40	1.44	.0119	.0906
SFEC	48	11.38	.29	1.68	.0027	.0949
Pooled error	6087	1770.27				
Total	6300	3908.04				
Standard Deviation in Fractional Rate of Change						
Session (S)	3	2.29	.15	2.07	.1099	.1370
Initial flow rate (F)	2	1.57	.10	3.07	.0540	.0657
Initial edge rate (E)	4	.67	.04	.78	.5420	.4364
Initial fractional change (C)	2	.62	.04	1.61	.2094	.2161
Pooled error	6289	10.46				
Total	6300	15.61				

Table III-D-3 (Concluded)

Note. Each effect was tested using the appropriate error term given by the model. Main effects are reported without regard to the level of significance, but only interactions significant at the $p < .05$ level or better have been included. Greenhouse-Geisser connected probabilities $P_g < F$ have been included due to violations in the assumptions of homogeneity of covariance. An asterisk (*) indicates that the assumption was not violated.

CHAPTER IV

PERCEIVING AND CONTROLLING CHANGES IN ALTITUDE

Dean H. Owen and Lawrence Wolpert
The Ohio State University

The goals of the altitude-control experiment were similar to those for the initial study of speed control (Zaff & Owen, 1987): (a) to test the generalizability of results form earlier passive-judgment experiments (Hettinger et al., 1985; Owen, Warren, Jensen, & Mangold, 1981; Wolpert & Owen, 1985; Wolpert et al., 1983) to the active-control domain; (b) to determine the relative influences of flow rate and edge rate in the interfering effect of forward speed on sensitivity to loss in altitude found in earlier experiments (Hettinger et al., 1985; Owen & Freeman, 1987; Wolpert & Owen, 1985); and (c) to continue exploring the active-control paradigm as a technique for training individuals to attend to task-relevant information. Although several studies of visual information supporting continuous control of simulated self motion have been conducted previously (Mitchell, 1982; Warren & McMillan, 1984; Zacharias & Young, 1981), our goal again was precise manipulation of the optical conditions preceding individual control episodes.

The task used in the passive-judgment experiments required observers to distinguish events representing loss in altitude from events depicting level flight. If extended to the active-control situation, the correct state of affairs would be no control adjustment on the level trials. Since we are primarily interested in the effectiveness of control, requiring the individual to distinguish descent from ascent is more efficient experimentally, and should also make the task easier, resulting in a larger proportion of correct adjustments for analysis.

Method

Design. All test events represented flight at an initial altitude of 48 m over fields 48 m in width, so that global optical density perpendicular to the direction of travel (z/y_g) was 1 g/h. The edge rates ($\dot{x}/x_g$) required for the design were achieved by simulating fields that were 12, 24, 48, 96, or 192 m long, producing optical densities parallel to the direction of travel (z/x_g) of 0.25, 0.50, 1.00, 2.00, or 4.00g/h, respectively, in the lateral dimension. Two types of forcing functions were used, representing upward or downward wind shear, which resulted in ascent or descent at a constant rate ($\dot{z}$). The factorial design consisted of three levels of initial flow rate ($\dot{s}_o/z = 1.5$, 3.0, and 6.0 h/s) by three levels of edge rate ($\dot{x}/x_g = 1.5$, 3.0, and 6.0 edges/s) by two levels of initial fractional change in altitude ($\dot{z}_o/z = \pm 2$ and 4%/s) by the two event types (ascent and descent) by three level-flight preview durations (1.25, 2.50, and 5.00 s), resulting in 108 unique events. Preview period was varied to assess the effect of temporal uncertainty concerning the forcing-function onset. (See Johnson and Owen (1985) and Owen and Freeman (1987) for the effects of preview-period duration on sensitivity to loss in altitude.) Each event continued for 10 s after the end of the preview segment, with no warning signal between the segments.

Procedure. The participant was instructed to maintain a constant altitude by applying an appropriate force on the control in the forward direction to cancel ascent and the backward direction to cancel descent. Following the corrective adjustment, he was to maintain the resulting altitude for the remainder of the trial. Output of the force control was recorded every 1/30 of a second and scaled to serve as a single integrator controller on altitude (z). Application of a constant force resulted in addition of a constant sink- or climb-rate ($\dot{z}$) component to the forcing function. The resulting sum controlled changes in the scene every 1/30 of a second.

As a result of high error rates, particularly early adjustments during the constant-altitude preview period, feedback summarizing frequencies of early, wrong-direction, and no control actions was given prior to the second, third, and fourth test sessions. Participants were

29 male undergraduate students with no experience as a pilot. As in the Zaff and Owen (1987) speed-control experiment, the results will be presented in three sequential phases (see Figure III-3).

Results

Control initiation. The longer the preview period, the more premature control adjustments during the preview segment. These early responses decreased with feedback after the first session, and continued to decrease over the next three sessions. With increase in preview-duration, the proportion of wrong-direction control adjustments increased and reaction times decreased, a speed-accuracy tradeoff also observed in the passive-judgment experiments (Johnson & Owen, 1985; Owen & Freeman, 1987; Owen et al., 1985). Interactions of preview duration with other variables were minor.

Increasing flow rate had opposite effects on performance for the two types of forcing functions, as shown in Figure IV-1. Ascent control adjustments in the wrong direction increased by over 30% across the three flow rates, and reaction time on correct trials increased by over 1 s. Wrong-direction adjustments occurred much less frequently for descent and actually dropped by 5% as flow rate increased. Descent reaction time decreased only slightly. In the passive-judgment experiments, increasing flow rate increasingly interfered with descent detection, as was found for ascent events in the present experiment. The contrasting results may be due to the difference in the context of the descent trials. They were contrasted with level flight in the judgment studies and with ascent in the active-control experiment. A reasonable explanation can be made in terms of what happens to flow rate during each event type: During ascent at a constant rate, flow rate decreases; during descent, flow rate increases. In parallel with the Zaff and Owen (1987) findings for deceleration and acceleration, higher flow rates would be erroneously taken to indicate flow acceleration on ascent trials, but lead to fewer errors on descent trials where flow actually accelerates. The problem with this account is that flow acceleration was not useful information for detecting descent in the judgment experiments. Either there was no difference between descent

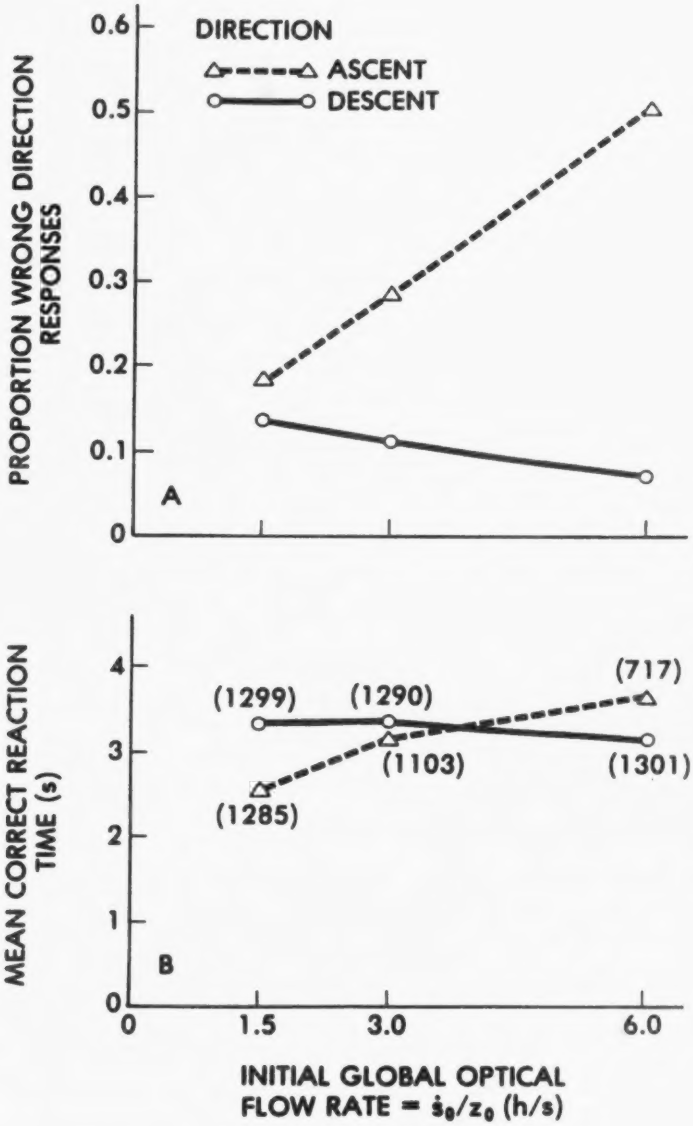

Figure IV-1. Proportion wrong direction responses and mean correct reaction time as a function of initial flow rate ($\dot{s}_0/z_0$) for events representing ascending and descending self motion. (Numbers in parentheses indicate observations per point.)

with constant flow and descent with accelerating flow (Hettinger et al., 1985), or accelerating flow made descent detection more difficult (Wolpert & Owen, 1985; Wolpert et al., 1983). Distinguishing descent from ascent may make change in flow rate more salient, however. Although further work will be necessary to clarify this interaction, it is clear that flow rate has a substantial effect on performance.

By contrast, the effects of edge rate were minimal. Over increases in edge rate, error rate dropped for ascent and increased for descent. The interaction with flow rate was more complex. When flow rate was 1.5 h/s, the highest edge rate resulted in 4% more wrong-direction errors than did the lowest edge rate. By the highest flow rate, the effect disappeared. The opposite interaction occurred for correct reaction time on ascent trials, with no difference at the lowest flow rate, but a 0.5-s effect favoring high edge rates for the two highest flow rates. Descent reaction time showed this pattern only at the highest flow rate. In summary, when edge rate has an effect, it is to increase errors but decrease reaction time. It is reasonable for errors to increase as effective information-acquisition time is reduced, but optical variables have not previously resulted in speed-accuracy trade-offs.

As expected, performance was better at the higher fractional rate of change. As a secondary independent variable (Warren & Owen, 1982), global optical density had no effect on errors beyond that manifested indirectly via edge rate. Densities of 1 to 2g/h were optimal for reaction time. Preview duration effects paralleled those found in the earlier studies (Johnson & Owen, 1985; Owen & Freeman, 1987): As preview duration increased, errors increased and reaction times decreased. Increasing waiting time produces a speed-accuracy trade-off. Temporal uncertainty leads to anticipatory actions without allowing the event to unfold sufficiently for accurate guidance of the adjustment. Errors of putting pressure on the control in the wrong direction decreased from 29% in the first session to 15% in the fourth. The interfering effect of flow rate showed none of the decrease with practice found by giving advance information before each trial (Hettinger, 1987; Hettinger & Owen, 1985). Global feedback was effective in reducing early, uninformed control adjustments during the preview period but had no effect of reducing attention to irrelevant information.

Slope of initial correction. Figure IV-2 shows the major influence on the initial control-onset ramp. Fractional change in altitude, the functional variable for detection of descent (Owen et al., 1981), affects the rate at which the forcing function is cancelled. The slope of the ramp is acceleration in altitude change ($\ddot{z}$), the next derivative above that controlled (z) in order to maintain a constant altitude (z). The higher the fractional loss, the steeper the slope, and the longer it takes to cancel the forcing function. It is interesting to note the small differences due to event type, even though fractional change accelerates during descent and decelerates during ascent. Flow rate also affected the slope, but the effect was much smaller. The higher the flow rate, the steeper the control-onset slope, suggesting that the individual feels more certain of what to do even though flow rate is irrelevant.

Maintenance. Since the altitude maintained was largely a function of the altitude reached by the time the control action was initiated, the patterns of results for reaction time, mean altitude, and perspectival "road" angle were very similar. As a consequence of these relationships, the longer the preview period, the nearer the maintained altitude was to the original altitude. Change in altitude ($\dot{z}$), the sum of the forcing function and the controller output, was less dependent on initial conditions. Figure IV-3 shows that the effect of flow rate on mean change in altitude was greater for descent than ascent and opposite in direction. When compared with the error rates in Figure IV-1, we again see the correspondence between sensitivity and effectiveness: What is easier to detect, is easier to control. Within the ascent condition, the higher the edge rate, the poorer the control. The effect of edge rate on descent control was less clear, but generally opposite. Overall, it appears that high flow and edge rates are both confused with flow acceleration, an account that would converge with the error data. Curiously, mean change in altitude increasingly deviated from the desired goal ($\dot{z} = 0$ m/s) with practice (see Figure IV-4). There was a pronounced tendency to overcompensate for the forcing function, and this

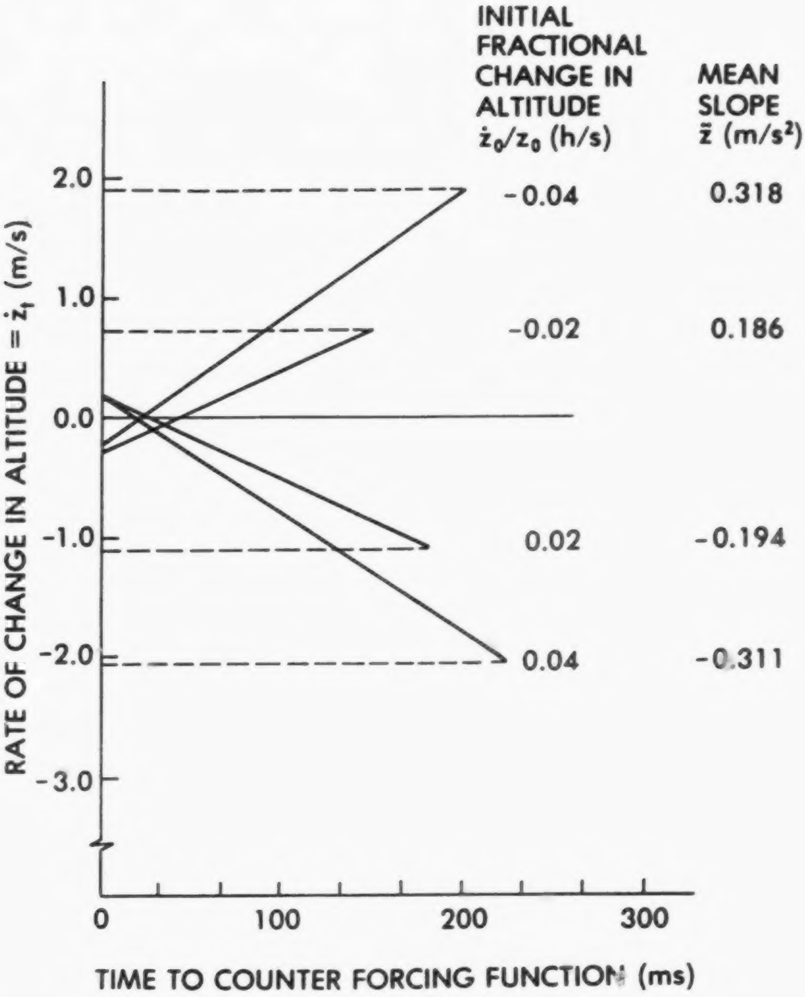

Figure IV-2. Regression lines for controlled change in altitude from reaction time until the forcing function had been countered (at the dashed line) for each level of initial fractional change in altitude. The slope of each line is equal to the change in sink or climb rate ($\ddot{z}$) during the initial correction phase of performance.

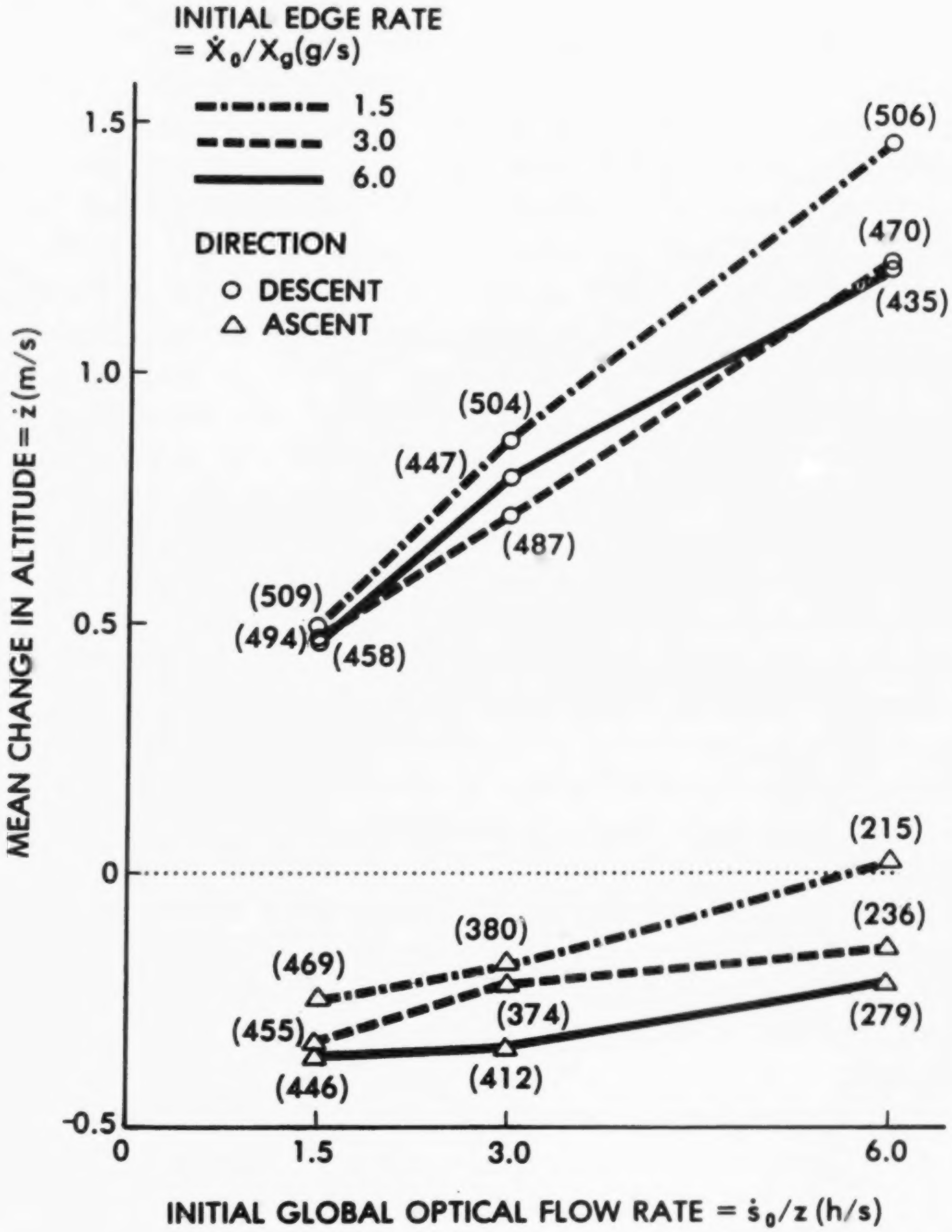

Figure IV-3. Mean change in altitude ($\dot{z}$) as a function of initial flow rate ($\dot{s}_0/z$) and edge rate ($\dot{x}_0/x_g$) for events representing ascending and descending self motion. (Numbers in parentheses indicate observations per point.)

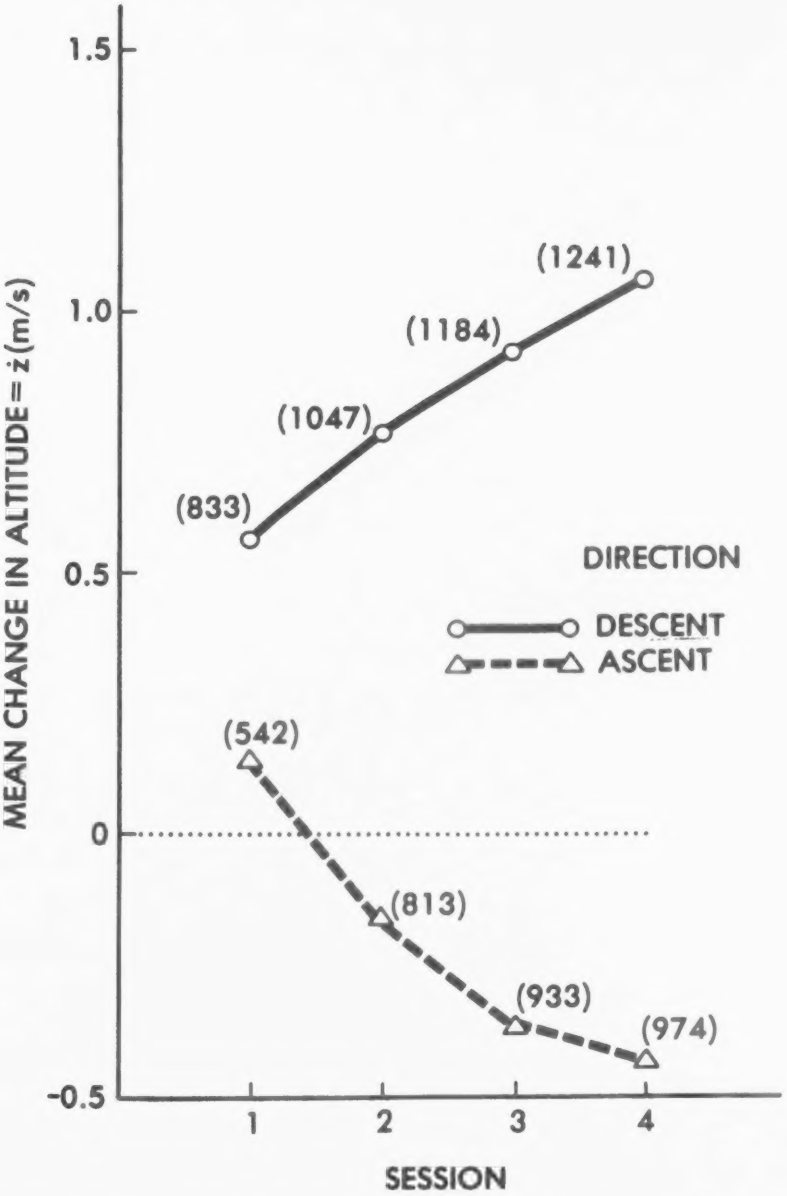

Figure IV-4. Mean change in altitude ($\dot{z}$) as a function of sessions for events representing ascending and descending self motion. (Numbers in parentheses indicate observation per point.)

overcontrol continued during maintenance. It appears that as sensitivity to task-relevant variables improves with practice, overcontrol of those variables may be a byproduct. Because of its implications for training, this result deserves further attention.

Conclusions

Gibson (1966, 1979) proposed replacing causal theories of perception with the idea of a chain of specificities. Working backward, knowledge gained by perceiving is specific to the structure of the ambient array, which in turn is physically, lawfully specific to the structure of the environment and the individual's relation to it. If this chain of specificities holds, then controlling the information in the ambient array effectively will result in achieving intended relationships between the individual and the environment. The experiments presented support the idea that optic array transformations and invariants are informative. But they can also be uninformative or misinformative, depending on the attunement of the individual to task-relevant and irrelevant types of information. The results indicate that the effects of optical variables can be detected experimentally in a variety of ways, and that unanticipated effects can be gleaned from examination of performance time series. For example, although the *acquisition* of self-motion information ordinarily takes several seconds, the intention of an individual can be determined from the first 100 ms of *control*. The effects of optical variables on such a limited sample of performance indicate that the individual knows with a high, though varying, degree of certainty *what* he is attempting to control, even if he is wrong.

The major reason for the development of visual simulation technology is not for research but rather, for training. Improvement in sensitivity to and control of optical variables is certain to be an important part of learning to control a vehicle. The results described demonstrate that evidence of improved attunement to relevant optical variables and decreased attunement to irrelevant variables can be found at every phase in the perception-action cycle. Analysis of the relation between optical variables and performance can help a researcher diagnose the locus of a problem in the cycle, so that practice and/or instruction can be concentrated there.

Given the principle that one cannot control what one is insensitive to, a test for the ability to detect functional variables might be a first step in diagnosis. Instructional procedures might then be developed to improve sensitivity before articulating control skills. Initial efforts in this direction have begun by manipulating the kind of training (advance information feedback, active control) and the scene content used for training (Hettinger, 1987; Hettinger & Owen, 1985; Warren & Riccio, 1985).

Isolation of what the trainee must become attuned to is a major consideration in optimizing the early stages in acquiring control skills (Owen, 1987a). If, as some of our results suggest, individuals can learn directly from the optical consequences of their own control actions, "shaping" performance by successively approaching operational conditions may be all that is needed for transfer from the simulated environment to the real world. Extrinsic feedback may speed the acquisition, or, if it fails to take into account differences in sensitivity and control skills between trainee and instructor, such feedback may even interfere.

In concluding his last book, Gibson (1979, p. 306) argued that psychophysics is adequate to the task of understanding ecological perception only if we consider the relevant dimensions of information in the flowing array of stimulation. The experiments reviewed demonstrate that the logic of psychophysics can be useful, if modified and adapted to ecological problems. The discovery that equal-ratio increments in a functional (task-relevant, informative) variable result in equal-interval improvements in performance (reduction in errors and reaction times) illustrates an ecological form of a Fechnerian principle (see Fechner (1860/1966) for his psychophysical "law"). Determination of the adequate level of a functional variable to support performance of a particular task, and determination of the level at which to introduce a dysfunctional (interfering, misinformative) variable that must be ignored in the real world, are examples of ecological thresholds. But, an understanding of sensitivity, though essential, is not sufficient.

We do not simply respond to stimuli. The criterion for skillful behavior is effective control of the informative structure of stimulation, and its study requires an active psychophysics that treats transformations and invariants in the ambient array as dependent variables. The experiments reported represent seminal steps in the development of an interactive paradigm for the study of self-motion perception and control.

APPENDIX IV-A: INVENTORY OF FLIGHT AND TEXTURE PARAMETERS

Table IV-A-1. Inventory of Flight Parameters[a]

Filename	SR	ETime	PTime	z_0	$\dot{z}_0$	$\ddot{z}_0$	$R_{\dot{z}}$	$\dot{x}_0$	$\ddot{x}_0$	$R_{\dot{x}}$
019001.DAC	30	10.0	0.0	48	-0.96	0	1	72	0	1
019002.DAC	30	10.0	0.0	48	-0.96	0	1	144	0	1
019003.DAC	30	10.0	0.0	48	-0.96	0	1	288	0	1
019004.DAC	30	10.0	0.0	48	-1.92	0	1	72	0	1
019005.DAC	30	10.0	0.0	48	-1.92	0	1	144	0	1
019006.DAC	30	10.0	0.0	48	-1.92	0	1	288	0	1
019007.DAC	30	10.0	0.0	48	0.96	0	1	72	0	1
019008.DAC	30	10.0	0.0	48	0.96	0	1	144	0	1
019009.DAC	30	10.0	0.0	48	0.96	0	1	288	0	1
019010.DAC	30	10.0	0.0	48	1.92	0	1	72	0	1
019011.DAC	30	10.0	0.0	48	1.92	0	1	144	0	1
019012.DAC	30	10.0	0.0	48	1.92	0	1	288	0	1
019013.DAC	30	12.5	2.5	48	-0.96	0	1	72	0	1
019014.DAC	30	12.5	2.5	48	-0.96	0	1	144	0	1
019015.DAC	30	12.5	2.5	48	-0.96	0	1	288	0	1
019016.DAC	30	12.5	2.5	48	-1.92	0	1	72	0	1
019017.DAC	30	12.5	2.5	48	-1.92	0	1	144	0	1
019018.DAC	30	12.5	2.5	48	-1.92	0	1	288	0	1
019019.DAC	30	12.5	2.5	48	0.96	0	1	72	0	1
019020.DAC	30	12.5	2.5	48	0.96	0	1	144	0	1
019021.DAC	30	12.5	2.5	48	0.96	0	1	288	0	1

Table IV-A-1 (Continued)

Filename	SR	ETime	PTime	z_0	$\dot{z}_0$	$\ddot{z}_0$	$R_{\dot{z}}$	$\dot{x}_0$	$\ddot{x}_0$	$R_{\dot{x}}$
019022.DAC	30	12.5	2.5	48	1.92	0	1	72	0	1
019023.DAC	30	12.5	2.5	48	1.92	0	1	144	0	1
019024.DAC	30	12.5	2.5	48	1.92	0	1	288	0	1
019025.DAC	30	15.0	5.0	48	-0.96	0	1	72	0	1
019026.DAC	30	15.0	5.0	48	-0.96	0	1	144	0	1
019027.DAC	30	15.0	5.0	48	-0.96	0	1	288	0	1
019028.DAC	30	15.0	5.0	48	-1.92	0	1	72	0	1
019029.DAC	30	15.0	5.0	48	-1.92	0	1	144	0	1
019030.DAC	30	15.0	5.0	48	-1.92	0	1	288	0	1
019031.DAC	30	15.0	5.0	48	0.96	0	1	72	0	1
019032.DAC	30	15.0	5.0	48	0.96	0	1	144	0	1
019033.DAC	30	15.0	5.0	48	0.96	0	1	288	0	1
019034.DAC	30	15.0	5.0	48	1.92	0	1	72	0	1
019035.DAC	30	15.0	5.0	48	1.92	0	1	144	0	1
019036.DAC	30	15.0	5.0	48	1.92	0	1	288	0	1
019037.DAC	30	15.0	5.0	48	0.00	0	1	60	0	1
019038.DAC	30	15.0	5.0	48	-3.00	0	1	60	0	1
019039.DAC	30	15.0	5.0	48	3.00	0	1	60	0	1

Table IV-A-1 (Concluded)

Note. A dot over a symbol indicates a derivative with respect to time. A subscript of zero indicates the value of a variable at the initiation of an event, whereas a subscript of t indicates the value of a variable at any time during the event.

[a]Parameters

SR - sampling rate

ETime - event duration (s)

PTime - preview period duration (s)

z - altitude (m)

$\dot{z}$ - climb or sink rate (m/s)

$\ddot{z}$ - change in climb or sink rate (m/s^2)

$R_{\dot{z}}$ - gain in change in altitude

$\dot{x}_0$ - initial forward velocity (m/s)

$\ddot{x}$ - acceleration rate (m/s^2)

$R_{\dot{x}}$ - gain in change in velocity

Table IV-A-2. Inventory of Ground-Texture Parameters[a]

Filename	X_g	Y_g
019001.TEX	12	48
019002.TEX	24	48
019003.TEX	48	48
019004.TEX	96	48
019005.TEX	192	48

[a] Parameters

X_g - ground-texture dimension in direction parallel to the direction of travel (m).

Y_g - ground-texture dimension in direction perpendicular to the direction of travel (m).

APPENDIX IV-B: INSTRUCTIONS

INSTRUCTIONS FOR INTERACTIVE FLIGHT SIMULATION - ALTITUDE CONTROL

Welcome to the Aviation Psychology Laboratory. We are presently conducting research to assess the relative influences of various visual factors on your ability to control simulated self motion. We want to determine how well you can visually detect and control changes in simulated self motion in the absence of other sources of information which typically accompany self motion.

Each trial will consist of a computer-generated event on the screen representing forward travel in an airplane over open, flat fields. Your task is to maintain a constant altitude at all times. On each trial, you will encounter wind shear which will cause your altitude to either decrease or increase. As soon as you detect a decrease or an increase in altitude, adjust the control by applying an appropriate force in the appropriate direction, so that you cancel the change and maintain a constant altitude.

The force control, identical to those currently used in high performance aircraft, electronically records the amount of force that you apply while either gently pushing or pulling on the stick. Although it is very sensitive, the stick itself will not actually move. It controls the altitude of simulated flight by decreasing your altitude if you push the stick forward, or increasing your altitude if you pull back on the stick. You will be given four 15-second practice trials at the beginning of each test session so that you may become acquainted with the force control and the dynamics of your simulated flight. On the first two trials, the only change in altitude that will occur is the change that you cause with the control stick. The third practice trial will simulate loss in altitude; and the fourth, gain in altitude. The remaining events will be a random sequence of test trials in which you are required to detect a change in altitude, and to apply a force with a direction and magnitude that will exactly counter the change in order to maintain a constant altitude.

The specific procedure is as follows:

1. Before the beginning of each event, you will hear a "beep" in the

headset. At that time, turn your full attention to the screen.

2. The event will begin with a preview period of constant-altitude flight for 1 to 5 seconds, followed by a 10-second test period during which you must maintain a constant altitude. After the preview period, you will encounter either an increase or decrease in your altitude. Remember, you are required to maintain a constant altitude; so, as soon as you detect a change in your altitude you must correct for the change by applying a force to counter it in order to maintain as close to a constant altitude as you can for the remainder of the trial.
3. To repeat, when you see that you are gaining altitude, push the stick forward in order to level off. When you detect that you are losing altitude, pull the stick back in order to maintain constant altitude. Do not touch the control stick until you detect a change in altitude; it is very sensitive to any force that you apply.
4. The experiment consists of 112 trials, including the four practice trials at the beginning of each test session, during which you are to become acquainted with the dynamics of the force control stick. The first two practice trials will simulate constant-altitude flight, the third will lose altitude, and the fourth will gain altitude. Then the test trials will begin.

Do you have any questions?

If you have any questions about the procedure during the practice trials you should feel free to ask.

APPENDIX IV-C: ANALYSIS OF VARIANCE TABLES

Table IV-C-1. Analyses of Variance

Source	df	SS	R^2(%)	F	p<F
Wrong Direction Responses					
Session (S)	2	7.16	0.53	12.50	.0000
Initial flow rate (F)	2	27.35	2.04	26.11	.0000
Initial fractional change (C)	1	8.50	0.63	46.97	.0000
Direction (D)	1	65.06	4.85	17.23	.0003
Preview (P)	2	14.43	1.08	33.59	.0000
FD	2	60.26	4.49	35.56	.0000
ED	2	3.89	0.29	11.01	.0001
PC	2	0.58	0.04	3.45	.0396
PD	2	1.38	0.10	4.07	.0230
SFP	8	1.37	0.10	2.16	.0320
FEG	12	3.08	0.23	2.19	.0177
FPD	4	2.47	0.18	7.21	.0000
SFEPG	48	5.82	0.43	1.56	.0124
SEPCG	24	3.54	0.26	1.81	.0147
FEPDG	24	3.51	0.26	1.66	.0333
Pooled Error	536	1132.29	84.49	---	-----
Total	672	1340.69	100.00	---	----

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
Early Responses					
Session (S)	2	15.68	2.23	13.81	.0000
Initial flow rate (F)	2	2.59	0.37	3.42	.0404
Initial edge rate (E)	2	2.00	0.28	14.38	.0000
Preview (P)	2	57.71	8.20	51.00	.0000
SP	4	5.85	0.83	9.11	.0000
FE	4	0.62	0.09	4.06	.0043
FP	4	2.48	0.35	3.84	.0061
EP	4	2.12	0.30	8.13	.0000
SPR	12	1.39	0.20	2.57	.0030
FEG	12	0.97	0.14	2.13	.0210
FEP	8	0.92	0.13	2.22	.0275
SPRG	36	2.39	0.34	1.47	.0464
SFPRG	72	5.29	0.75	1.70	.0006
Pooled Error	508	603.54	85.79	---	-----
Total	672	703.55	100.00	---	-----
All Reaction Times except Early Reaction Times					
Initial flow rate (F)	2	808.36	2.26	7.62	.0021
Initial edge rate (E)	2	130.50	0.37	4.94	.0140
Initial fractional change (C)	1	1782.38	4.99	53.91	.0000
Preview (P)	2	2683.39	7.52	44.07	.0000

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
FE	4	67.37	0.19	3.89	.0072
FC	2	97.42	0.27	5.57	.0088
FD	2	586.98	1.64	18.32	.0000
FP	4	168.54	0.47	12.28	.0000
ED	2	193.27	0.54	14.11	.0000
DC	1	25.63	0.07	4.76	.0455
DG	3	387.21	1.08	3.81	.0326
PC	2	75.39	0.21	13.45	.0001
SFE	8	40.34	0.11	2.07	.0438
SFP	8	47.66	0.13	2.46	.0165
SEP	8	38.62	0.11	2.39	.0200
FED	4	50.54	0.14	3.38	.0148
FPC	4	38.31	0.11	3.10	.0220
FPD	4	27.85	0.08	3.09	.0222
EDG	6	142.60	0.40	3.47	.0100
EPC	4	31.26	0.09	3.80	.0081
PDC	2	20.16	0.06	3.73	.0357
FEPC	8	55.37	0.16	2.68	.0097
FEPD	8	117.10	0.33	4.01	.0003
SFEPC	16	70.59	0.20	1.74	.0403
FEPDC	8	50.20	0.14	2.44	.0177
FEPCG	24	109.36	0.31	1.76	.0248

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
Pooled Error	533	27856.37	78.02	---	-----
Total	672	35702.77	100.00	---	-----
		Ramp Slope (absolute)			
Inial flow rate (F)	2	2.62	0.36	6.73	.0030
Initial edge rate (E)	2	0.51	0.07	3.71	.0333
Initial fractional change (C)	1	22.30	3.03	45.96	.0000
Direction (D)	1	6.38	0.87	7.38	.0133
Preview (P)	2	0.92	0.13	3.25	.0494
FD	2	2.00	0.27	3.87	.0291
DC	1	3.06	0.42	8.97	.0071
SFG	12	1.92	0.26	2.20	.0190
FDC	2	1.16	0.16	4.22	.0217
SFCG	12	2.21	0.30	2.15	.0226
EPDC	4	0.67	0.09	3.67	.0086
SFPCG	24	2.22	0.30	1.82	.0162
EPDCG	12	1.26	0.17	2.29	.0147
Pooled Error	595	688.32	93.57	---	-----
Total	672	735.55	100.00	---	-----

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
		Mean Altitude			
Initial flow rate	2	46171.90	8.93	36.53	.0000
Initial edge rate	2	1641.64	0.32	10.96	.0002
Direction (D)	1	93335.55	18.06	91.34	.0000
Preview (P)	2	2277.77	0.44	15.33	.0000
FD	2	2684.30	0.52	13.73	.0000
FP	4	849.07	0.16	5.89	.0004
ED	2	337.22	0.07	5.61	.0073
DC	1	9889.28	1.91	74.56	.0000
PD	2	3783.17	0.73	30.16	.0000
SFP	8	442.41	0.09	2.09	.0399
FEP	8	555.04	0.11	2.48	.0148
FED	4	672.57	0.13	5.81	.0004
FDC	2	466.82	0.09	5.13	.0107
FCG	6	357.22	0.07	2.50	.0390
PDC	2	158.64	0.03	4.51	.0175
FEPDG	24	1187.22	0.23	1.85	.0137
SFEPC	16	524.97	0.10	1.77	.0338
SFEPDC	16	648.45	0.13	2.04	.0110
Pooled Error	568	351380.89	67.88	---	-----
Total	672	516864.13	100.00	---	-----

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
Mean Change in Altitude					
Initial flow rate (F)	2	3349.76	9.56	28.27	.0000
Initial edge rate (E)	2	153.48	0.44	18.07	.0000
SD	2	120.47	0.34	6.43	.0039
FD	2	413.57	1.18	16.71	.0000
DC	1	99.82	0.28	18.07	.0004
PD	2	122.35	0.35	13.17	.0000
SFP	8	41.65	0.12	2.09	.0400
FPD	4	18.21	0.05	2.76	.0335
SEPDC	8	35.62	0.10	2.08	.0414
SFEPDC	16	67.24	0.19	2.07	.0097
FEPDG	24	104.93	0.30	1.79	.0192
Pooled Error	601	30511.44	87.09	---	-----
Total	672	35038.54	100.00	---	-----
Mean Fractional Change in Altitude					
Initial flow rate (F)	2	0.69	0.28	7.80	.0015
Initial edge rate (E)	2	0.29	0.12	4.24	.0219
PD	2	0.28	0.11	4.29	.0210
Pooled Error	666	243.95	99.49	---	-----
Total	672	245.21	100.00	---	----

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
Mean Road Angle					
Initial flow rate (F)	2	8.35	6.46	34.99	.0000
Initial edge rate (E)	2	0.62	0.48	13.05	.0000
Initial fractional change (C)	1	0.11	0.08	6.71	.0179
Direction (D)	1	23.76	18.37	80.65	.0000
Preview (P)	2	0.38	0.28	11.50	.0001
SF	4	0.12	0.10	2.71	.0361
FD	2	0.26	0.21	5.12	.0107
FP	4	0.19	0.14	5.11	.0011
ED	2	0.10	0.07	5.71	.0068
DC	1	2.73	2.11	66.01	.0000
PD	2	1.02	0.79	32.02	.0000
SFC	4	0.05	0.04	2.78	.0327
FED	4	0.13	0.10	3.51	.0110
FEP	8	0.14	0.11	2.26	.0263
FDC	2	0.10	0.08	3.28	.0487
EDC	2	0.04	0.03	5.31	.0092
PDC	2	0.42	0.03	4.63	.0158
PDCG	6	0.18	0.06	2.97	.0178
FEPDG	24	0.30	0.23	1.73	.0252
SFEPDC	16	0.19	0.15	2.16	.0064
Pooled Error	581	90.13	70.08	---	-----

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
Total	672	129.32	100.00	---	-----
Mean Change in Road Angle					
Initial flow rate (F)	2	.226	4.49	34.82	.0000
Initial edge rate (E)	2	.040	0.80	15.53	.0000
Preview (P)	2	.008	0.16	5.74	.0066
SD	2	.028	0.56	7.41	.0019
FC	2	.002	0.06	3.21	.0514
DC	1	.009	0.18	4.02	.0594
PD	2	.033	0.66	17.73	.0000
EDC	2	.002	0.05	5.30	.0093
FEPDG	24	.015	0.30	1.58	.0513
SFEPDC	16	.011	0.22	1.78	.0326
Pooled Error	617	4.660	92.52	---	-----
Total	672	5.030	100.00	---	-----
Mean Standard Deviation in Altitude					
Initial flow rate (F)	2	2751.10	7.50	25.78	.0000
Initial edge rate (E)	2	58.14	0.16	5.52	.0079
Preview (P)	2	965.12	2.63	52.46	.0000
EP	4	41.23	0.11	5.51	.0006
PD	2	23.80	0.06	4.14	.0236

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
SPC	4	20.18	0.06	3.70	.0083
FPD	4	54.64	0.15	5.72	.0004
ECG	6	32.18	0.17	3.25	.0112
EDC	2	24.60	0.07	8.10	.0012
EPD	4	31.58	0.09	3.47	.0116
SFEG	24	80.85	0.22	1.85	.0141
SPDC	4	23.20	0.06	2.94	.0256
FEDC	4	16.94	0.05	2.98	.0241
SFEPG	48	153.62	0.42	1.55	.0155
SEDCG	12	29.38	0.08	1.95	.0415
FEDCG	12	37.98	0.10	2.23	.0181
Pooled Error	536	32328.75	88.07	---	-----
Total	672	36673.29	100.00	---	-----
Mean Standard Deviation in Altitude Change					
Initial flow rate (F)	2	112.66	1.51	15.45	.0000
Preview (P)	2	17.73	0.24	7.12	.0024
EP	4	7.27	0.10	5.23	.0009
PC	2	3.09	0.04	3.27	.0490
FED	4	6.61	0.09	3.73	.0080
EDC	2	2.91	0.04	3.45	.0420
SDG	6	10.21	0.14	2.48	.0399

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
SPCG	12	10.40	0.14	2.37	.0119
FEPG	24	17.18	0.23	1.64	.0401
Pooled Error	614	7248.16	97.47	---	-----
Total	672	7436.62	100.00	---	-----
Mean Standard Deviation in Fractional Change in Altitude					
GROUP (G)	3	1.76	0.20	3.96	.0239
Pooled Error	669	1390.38	99.80	---	-----
Total	672	1392.14	100.00	---	-----
Mean Standard Deviation in Road Angle					
Initial flow rate (F)	2	0.28	2.24	19.31	.0000
Initial edge rate (E)	2	0.06	0.45	9.68	.0004
Direction (D)	1	0.19	1.55	11.61	.0030
Preview (P)	2	0.24	1.97	49.82	.0000
ED	2	0.02	0.16	5.86	.0060
EP	4	0.03	0.21	6.36	.0002
DC	1	0.04	0.29	18.47	.0004
SPC	4	0.01	0.05	2.71	.0364
FPD	4	0.02	0.18	7.06	.0001
EDC	2	0.02	0.14	14.55	.0000
EPD	4	0.02	0.19	5.12	.0010

Table IV-C-1 (Continued)

Source	df	SS	R^2(%)	F	p<F
Pooled Error	644	11.32	92.57	---	-----
Total	6722	12.25	100.00	---	-----
Mean Standard Deviation in Road Angle Change					
Initial flow rate (F)	2	.056	1.76	17.62	.0000
Preview (P)	2	.007	0.22	4.61	.0161
FD	2	.006	0.20	3.94	.0280
ED	2	.003	0.08	4.07	.0250
EP	4	.004	0.13	4.58	.0023
PC	2	.002	0.07	6.16	.0048
FED	4	.002	0.09	2.58	.0436
FPD	4	.003	0.09	2.66	.0393
PCG	6	.004	0.12	3.53	.0071
EPDC	4	.003	0.10	3.49	.0114
Pooled Error	640	3.100	97.14	---	-----
Total	672	3.190	100.00	---	-----

REFERENCES

Clark, M. R., & Stark, L. (1975). Time optimal behavior of human saccadie eye movement. IEEE Transactions on Automatic Control, 20, 345-348.

Denton, G. G. (1973). A study of motion induced percepts of velocity. Unpublished doctoral dissertation, University of Southhampton.

Denton, G. G. (1974). Motion - a study of induced percepts of velocity (CSIR Special Report PERS 213). Johannesburg, South Africa: National Institute for Personnel Research, Council for Scientific and Industrial Research.

Denton, G. G. (1976). The influence of adaption on subjective velocity for an observer in simulated rectilinear motion. Ergomonics, 19, 409-430.

Denton, G. G. (1977). Visual motion aftereffect induced by simulated rectilinear motion. Perception, 6, 711-718.

Epstein, W. (1978). Two factors in the perception of velocity at a distance. Perception & Psychophysics, 24, 105-114.

Epstein, W. (1982). Percept-percept coupling. Perception, 11, 75-83.

Epstein, W., & Cody, W. J. (1980). Perception of relative velocity: A revision of the hypothesis of relational determination. Perception, 9, 47-60.

Fechner, G. (1966). Elements of psychophysics, Vol. 1. (D. H. Howes & E. G. Boring, Eds., and H. E. Adler, Trans.). New York: Holt, Rinehart & Winston. (Original work published 1860)

Gibson, E. J. (1969). Principles of perceptual learning and development. New York: Appleton-Century-Crofts.

Gibson, J. J. (1958). Visually controlled locomotion and visual orientation in animals. British Journal of Psychology, 49, 182-194.

Gibson, J. J. (1966). The senses considered as perceptual systems. Boston: Houghton-Mifflin.

Gibson, J. J. (1979). The ecological approach to perception. Boston: Houghton-Mifflin.

Gibson, J. J., Olum, P., & Rosenblatt, F. (1955). Parallax and perspective during aircraft landings. American Journal of Psychology, 68, 372-385.

Held, R. (1965). Plasticity in sensory-motor systems. *Scientific American*, *213*, 84-94.

Hettinger, L. J. (1987). *The education of attention to information specifying loss in altitude*. Unpublished doctoral dissertation, The Ohio State University, Columbus, OH.

Hettinger, L. J., & Owen, D. H. (1985). Increasing sensitivity to optical information specifying loss in altitude. *Proceedings of the Third Symposium on Aviation Psychology* (pp. 483-490). Columbus, OH.

Hettinger, L. J., Owen, D. H., & Warren, R. (1985). Global optical flow pattern information for loss in altitude. In D. H. Owen (Ed.), *Optical and event-duration variables affecting self-motion perception* (AFHRL-TP-85-23, AD-A161 836, pp. 7-50). Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Johnson, A. E., & Owen, D. H. (1985). The influence of preview period on sensitivity to loss in altitude. In D. H. Owen (Ed.), *Optical and event-duration variables affecting self-motion perception* (AFHRL-TP-85-23, AD-A161-836, pp. 155-176), Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception*, *5*, 437-459.

Lee, D. N. (1980). The optic flow field: The foundation of vision. *Philosophical Transactions of the Royal Society of London*, *13290*, 169-179.

Mitchell, T. (1982). dynamic perception of computer generated visual information in an altitude control task. *Proceedings of the Human Factors Society-26th Annual Meeting*, 890-894.

Owen, D. H. (1978). The psychophysics of prior experience. In P. K. Machamer & R. G. Turnbull (Eds.), *Studies in perception: Interrelations in the histories of science and philosophy*. Columbus, Ohio: The Ohio State University Press.

Owen, D. H. (1987a). An ecological approach to learning: Simulation and the education of attention. To appear in J. C. Belland & W. D. Taylor (Eds.), *Technology and the future of education*. Unpublished manuscript, The Ohio State University, Department of Psychology, Columbus, OH.

Owen, D. H. (1987b). *The functional principles of perception*. Unpublished manuscript, The Ohio State University, Department of Psychology, Columbus, OH.

Owen, D. H. (Ed.). (1985). *Optical and event-duration variables affecting self-motion perception* (AFHRL-TP-85-23, AD-A161 836). Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Owen, D. H., & Freeman, S. J. (1987). Effects of preview duration, optical flow rate, and optical texture density on sensitivity to loss in altitude. In D. H. Owen (Ed.), *Optical and event-duration variables affecting the perception and control of self motion* (Final Technical Report for AFHRL Contract No. F33615-83-K-0038). Columbus, OH: The Ohio State University, Department of Psychology, Aviation Psychology Laboratory.

Owen, D. H., Hettinger, L. J., Pallos, I. E., & Fogt, J. C. (1985). The influence of preview period and global optical flow rate on sensitivity to decelerating self motion. In D. H. Owen (Ed.), *Optical and event-duration variables affecting self-motion perception* (AFHRL-TP-85-23, AD-A161 836). Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Owen, D. H., & Warren, R. (1982). Optical variables as measures of performance during simulated flight. *Proceedings of the Human Factors Society-26th Annual Meeting* (pp. 312-315).

Owen, D. H., Warren, R., Jensen, R. S., & Mangold, S. J. (1981). Optical information for detecting loss in one's own altitude. In D. H. Owen & R. S. Jensen (Eds.), *Methodological approaches to identifying relevant features for visual flight simulation* (Final Technical Report for AFOSR Contract No. F49620-79-C-0070, Task 1). Columbus, OH: The Ohio State University, Department of Psychology, Aviation Psychology Laboratory.

Owen, D. H., Warren, R., Jensen, R. S., Mangold, S. J., & Hettinger, L. J. (1981). Optical information for detecting loss in one's own forward speed. *Acta Psychologica*, *48*, 203-213.

Owen, D. H., & Wolpert, L. (1987). Perceiving and controlling changes in altitude. In D. H. Owen (Ed.), *Optical and event-duration variables affecting the perception and control of self motion* (Final Technical Report for AFHRL Contract No. F33615-83-K-0038). Columbus, OH: The Ohio State University, Department of Psychology, Aviation Psychology Laboratory.

Owen, D. H., Wolpert, L., & Warren, R. (1984). Effects of optical flow acceleration, edge acceleration, and viewing time on the perception of egospeed acceleration. In D. H. Owen (Ed.), *Optical flow and texture variables useful in detecting decelerating and accelerating self-motion* (AFHRL-TP-84-4, AD-A148 718). Williams, AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Pollack, I., Norman, D. A., & Galanter, E. (1964). An effecient non-parametric analysis of recognition memory. Psychonomic Science, 1, 327-328.

Rock, I. (1968). Speed constancy as a function of size constancy. Perception & Psychophysics, 4, 37-40.

Runeson, S. (1974). Constant velocity - not perceived as such. Psychological Research, 37, 3-23.

Runeson, S. (1975). Visual prediction of collision with natural and non-natural motion functions. Perception & Psychophysics, 18, 261-266.

Shaw, R. E., & Alley, T. R. (1985). How to draw learning curves: Their use and justification. In T. D. Johnston & A. T. Pietrewiecz (Eds.), Issues in the ecological study of learning. Hillsdale, NJ: Erlbaum.

Tobias, S. B. (1983). Optical information for the detection of decelerating self motion. Unpublished master's thesis, The Ohio State University, Columbus, OH.

Tobias, S. B., & Owen, D. H. (1984). Optical flow and texture variables useful in detecting decelerating self motion. In D. H. Owen (Ed.), Optical flow and texture variables useful in detecting decelerating and accelerating self motion (AFHRL-TP-84-4, AD-A148 718). Williams, AFB: AZ: Operations Training Division, Air Force Human Resources Laboratory.

Turvey, M. T., & Carello, C. (1981). Cognition: The view from ecological realism. Cognition, 10, 313-321.

Turvey, M. T., & Kugler, P. N. (1984). An ecological approach to perception and action. In H. T. A. Whitney (Ed.), Human motor actions - Berstein reassessed. North Holland: Elsevier Science.

Warren, R. (1982). Optical transformation during movement: Review of the optical concomitants of egomotion (Final Tech. Rep. for Grant No. AFOSR-81-0108). Columbus, OH: The Ohio State University, Department of Psychology, Aviation Psychology Laboratory.

Warren, R., & McMillan, G. R. (1984). Altitude control using action-demanding interactive displays: Toward an active psychophysics. Proceedings of the 1984 Image Conference III, 38-51.

Warren, R., & Owen, D. H. (1982). Functional optical invariants: A new methodology for aviation research. Journal of Aviation, Space, and Environmental Medicine, 53, 977-983.

Warren, R., Owen, D. H., & Hettinger, L. J. (1982). Separation of the contribution of optical flow rate and edge rate on the perception of egospeed acceleration. In D. H. Owen (Ed.), *Optical flow and texture variables useful in simulation self motion. (II).* (Interim Tech. Rep. for Grant No. AFOSR-81-0078, pp. 23-76). Columbus, OH: The Ohio State University, Department of Psychology.

Warren, R., & Riccio, G. E. (1985). Visual cue dominance hierarchies: Implications for simulator design. *Society of Automotive Engineers* (Technical Paper, No. 851946.)

Wolpert, L., & Owen, D. H. (1985). Functional and distracting information influencing the detection of loss in altitude. In D. H. Owen (Ed.), *Optical and event-duration variables affecting self-motion perception* (AFHRL-TP-85-23, AD-A161 836). Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory.

Wolpert, L., Owen, D. H. & Warren, R. (1983, June). The isolation of optical information and its metrics for the detection of descent. In D. H. Owen (Ed.), *Optical flow and texture variables useful in simulating self motion (II)* (Final Technical Report for Grant No. AFOSR-81-0078). Columbus, OH: The Ohio State University, Department of Psychology, Aviation Psychology Laboratory.

Yoshi, V. (1980). *A real time video display with dynamically alterable parameters.* Unpublished master's thesis, The Ohio State University, Columbus, OH.

Zacharias, G. L., & Young, L. R. (1981). Influence of combined visual and vestibular cues on human perception and control of horizontal rotation. *Experimental Brain Research, 41*, 159-171.

Zaff, B. Z., & Owen, D. H. (1987). Perceiving and controlling changes in the speed of self motion. In D. H. Owen (Ed.) *Optical and event-duration variables affecting the perception and control of self motion* (Final Technical Report for AFHRL Contract No. F33615-83-K-0038). Columbus, OH: The Ohio State University, Department of Psychology, Aviation Psychology Laboratory.

* GOVERNMENT PRINTING OFFICE: [illegible]